Institute of Applied Physics
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Optical Design with Zemax

Lecture 2: Properties of optical systems I

2012-10-23

Herbert Gross

2 Properties of Optical Systems I
Preliminary time schedule

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1	16.10.	Introduction	Introduction, Zemax interface, menues, file handling, preferences, Editors, updates, windows, Coordinate systems and notations, System description, Component reversal, system insertion, scaling, 3D geometry, aperture, field, wavelength
2	23.10.	Properties of optical systems I	Diameters, stop and pupil, vignetting, Layouts, Materials, Glass catalogs, Raytrace, Ray fans and sampling, Footprints
3	30.10.	Properties of optical systems II	Types of surfaces, Aspheres, Gratings and diffractive surfaces, Gradient media, Cardinal elements, Lens properties, Imaging, magnification, paraxial approximation and modelling
4	06.11.	Aberrations I	Representation of geometrical aberrations, Spot diagram, Transverse aberration diagrams, Aberration expansions, Primary aberrations,
5	13.11.	Aberrations II	Wave aberrations, Zernike polynomials, Point spread function, Optical transfer function
6	20.11.	Optimization I	Principles of nonlinear optimization, Optimization in optical design, Global optimization methods, Solves and pickups, variables, Sensitivity of variables in optical systems
7	27.11.	Optimization II	Systematic methods and optimization process, Starting points, Optimization in Zemax
8	04.12	Imaging	Fundamentals of Fourier optics, Physical optical image formation, Imaging in Zemax
9	11.12.	Illumination	Introduction in illumination, Simple photometry of optical systems, Non-sequential raytrace, Illumination in Zemax
10	18.12.	Advanced handling I	Telecentricity, infinity object distance and afocal image, Local/global coordinates, Add fold mirror, Scale system, Make double pass, Vignetting, Diameter types, Ray aiming, Material index fit
11	08.01.	Advanced handling II	Report graphics, Universal plot, Slider, Visual optimization, IO of data, Multiconfiguration, Fiber coupling, Macro language, Lens catalogs
12	15.01.	Correction I	Symmetry principle, Lens bending, Correcting spherical aberration, Coma, stop position, Astigmatism, Field flattening, Chromatical correction, Retrofocus and telephoto setup, Design method
13	22.01.	Correction II	Field lenses, Stop position influence, Aspheres and higher orders, Principles of glass selection, Sensitivity of a system correction, Microscopic objective lens, Zoom system
14	29.01.	Physical optical modelling I	Gaussian beams, POP propagation, polarization raytrace, polarization transmission, polarization aberrations
15	05.02.	Physical optical modelling II	coatings, representations, transmission and phase effects, ghost imaging, general straylight with BRDF

2 Properties of Optical Systems I
Contents 2nd Lecture

1. Diameters
2. Stops and Pupil definition
3. Vignetting
4. Layout
5. Materials and glass catalogs
6. Raytrace
7. Ray fans and sampling
8. Footprints

Optical system stop

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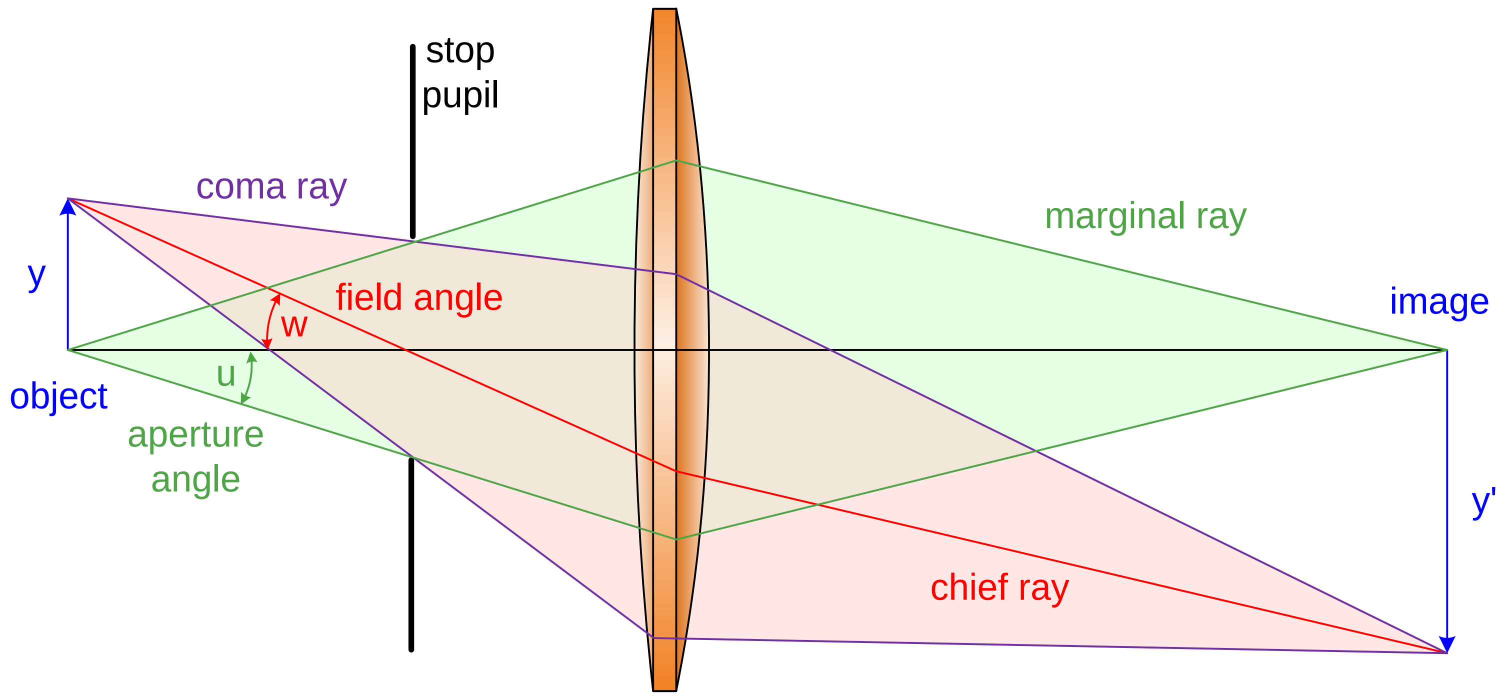
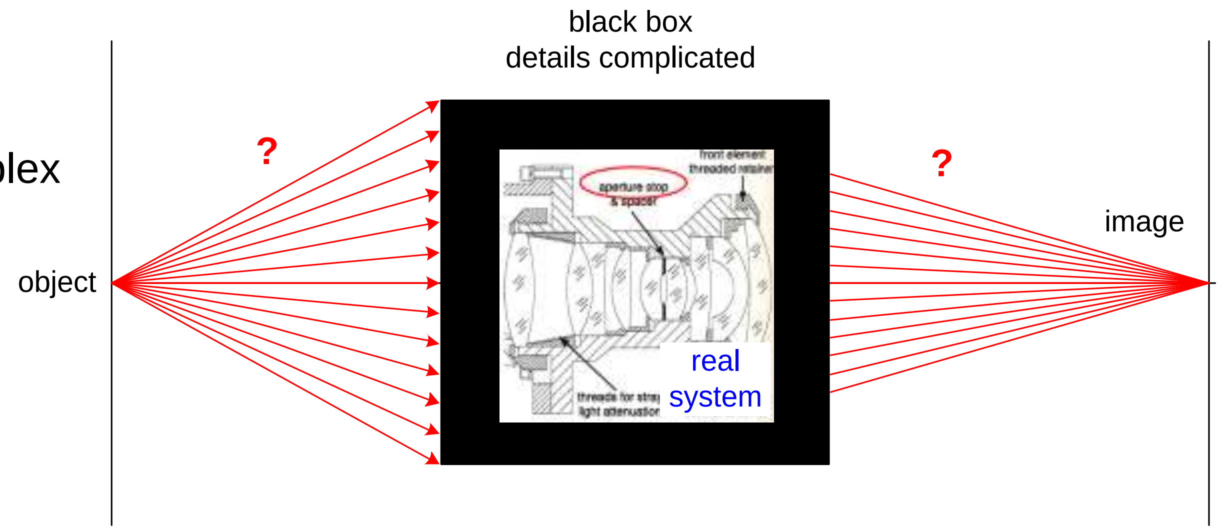
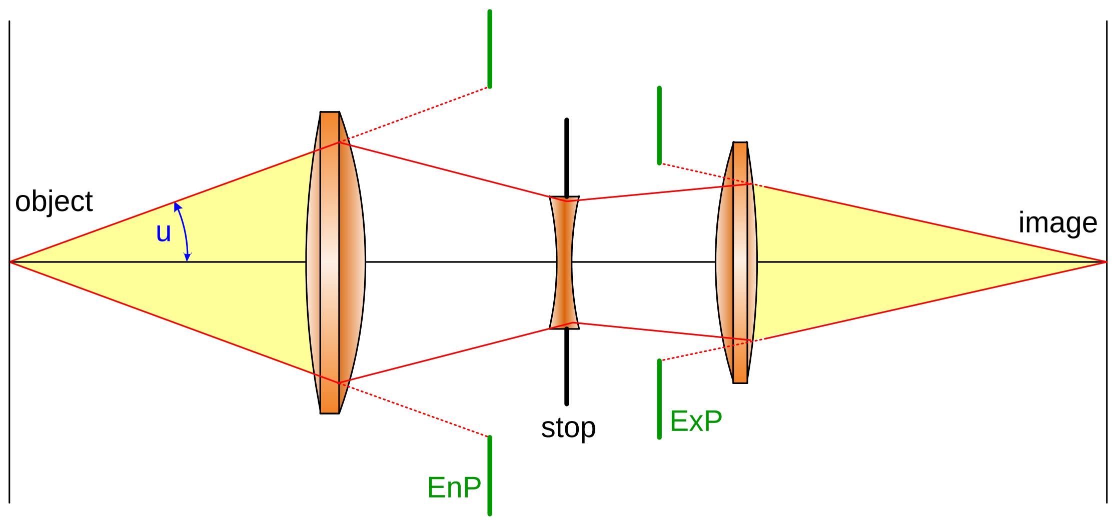
- Pupil stop defines:
  1. chief ray angle w
  2. aperture cone angle u
- The chief ray gives the center line of the oblique ray cone of an off-axis object point
- The coma rays limit the off-axis ray cone
- The marginal rays limit the axial ray cone



- The physical stop defines the aperture cone angle u
- The real system may be complex



- The entrance pupil fixes the acceptance cone in the object space
- The exit pupil fixes the acceptance cone in the image space



Ref: Julie Bentley

Properties of the pupil

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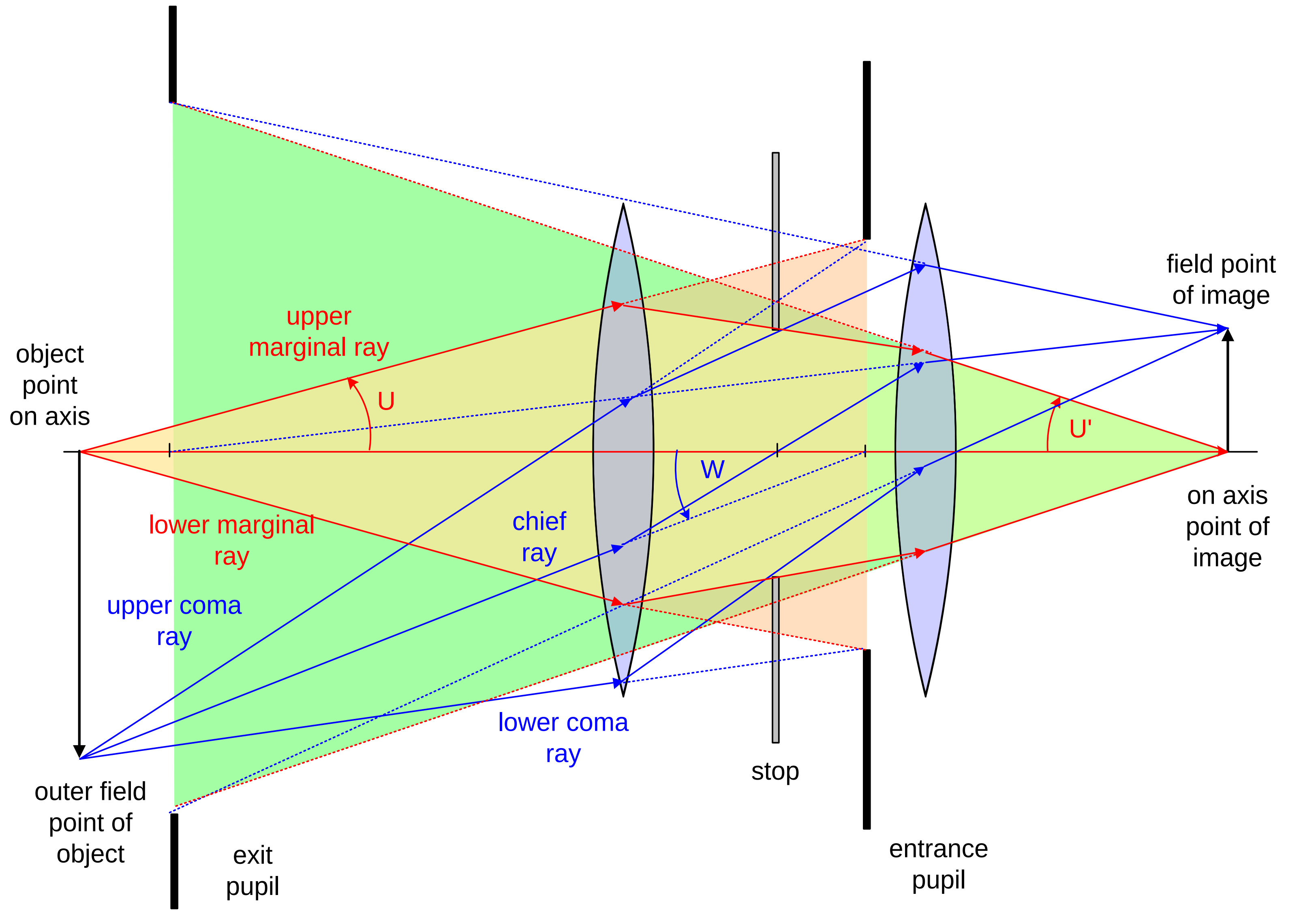
Relevance of the system pupil :

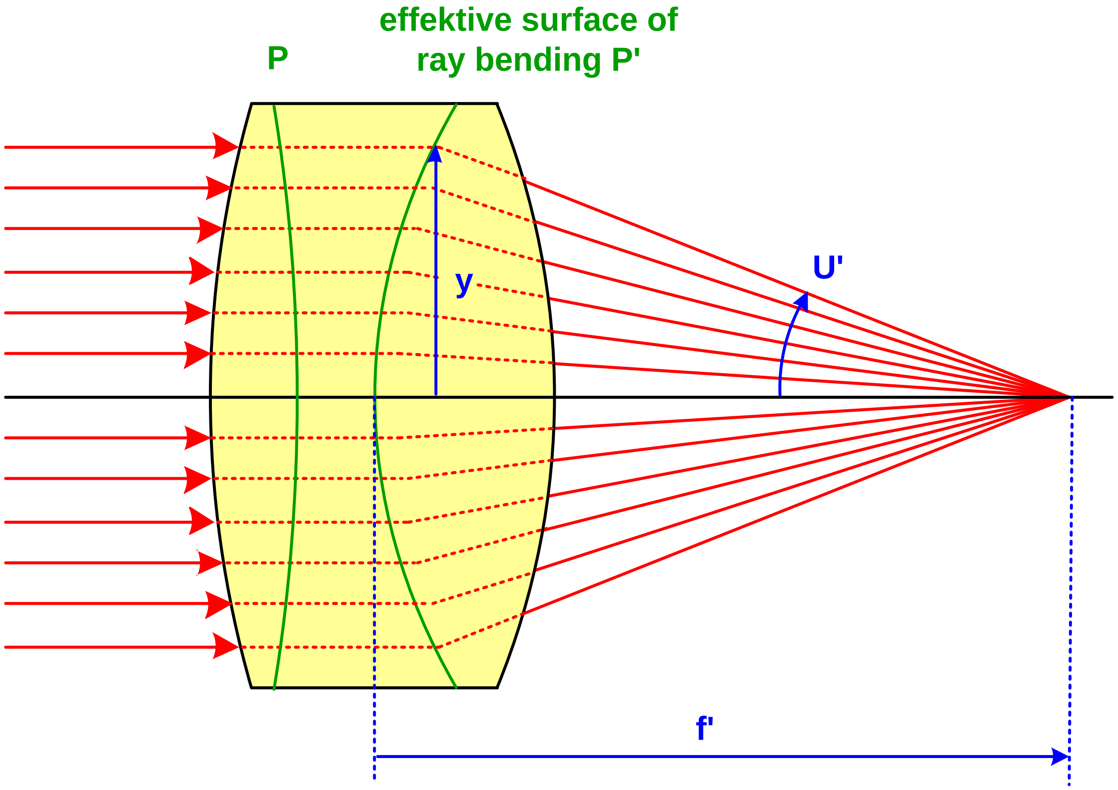
- Brightness of the image
  Transfer of energy
- Resolution of details
  Information transfer
- Image quality
  Aberrations due to aperture
- Image perspective
  Perception of depth
- Compound systems:
  matching of pupils is necessary, location and size

Entrance and exit pupil

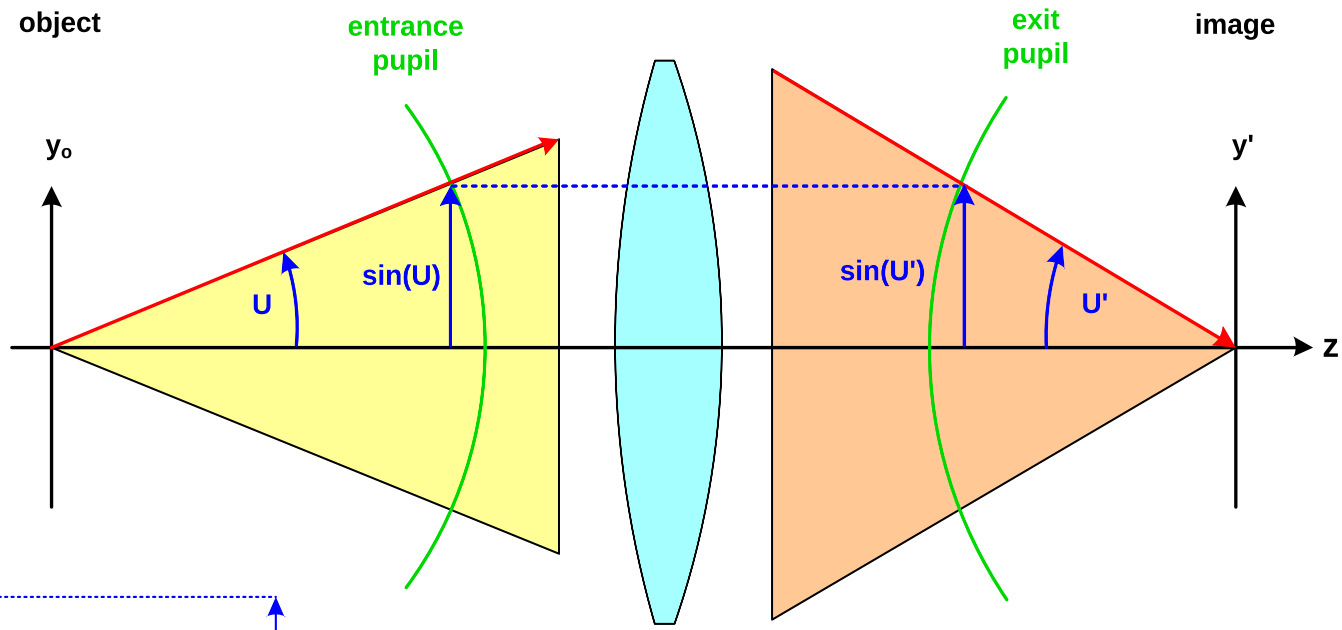


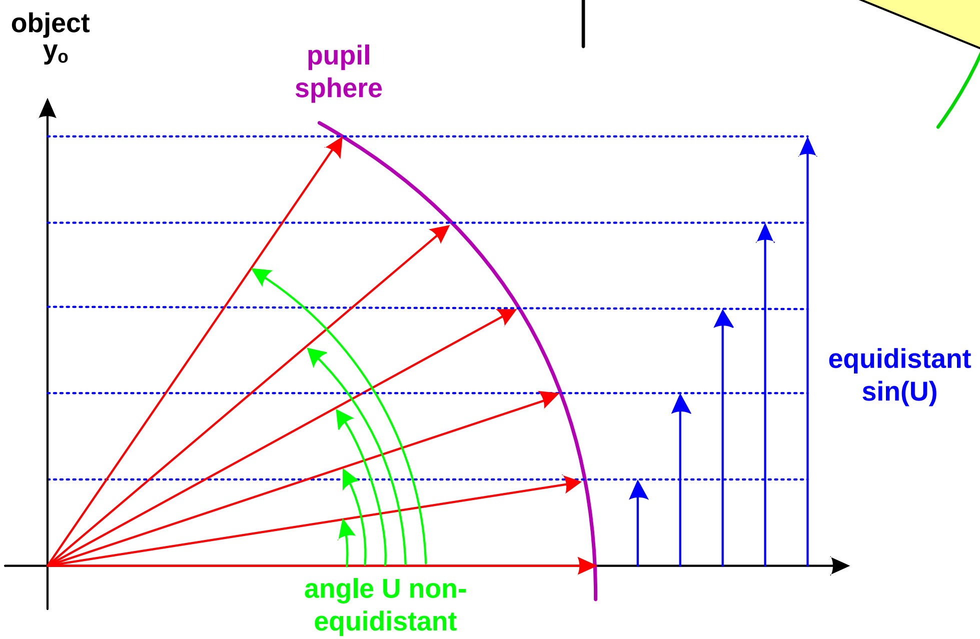
Pupil sphere

- Generalization of paraxial picture:
  Principal surface works as effective location of ray bending
- Paraxial approximation: plane
- Real systems with corrected sine-condition (aplanatic): principal sphere



- Pupil sphere: equidistant sine-sampling





2 Properties of Optical Systems I
Aperture data in Zemax

- Different possible options for specification of the aperture in Zemax:

1. Entrance pupil diameter
2. Image space F#
3. Object space NA
4. Paraxial working F#
5. Object cone angle
6. Floating by stop size

- Stop location:

1. Fixes the chief ray intersection point
2. input not necessary for telecentric object space
3. is used for aperture determination in case of aiming

- Special cases:

1. Object in infinity (NA, cone angle input impossible)
2. Image in infinity (afocal)
3. Object space telecentric

Vignetting

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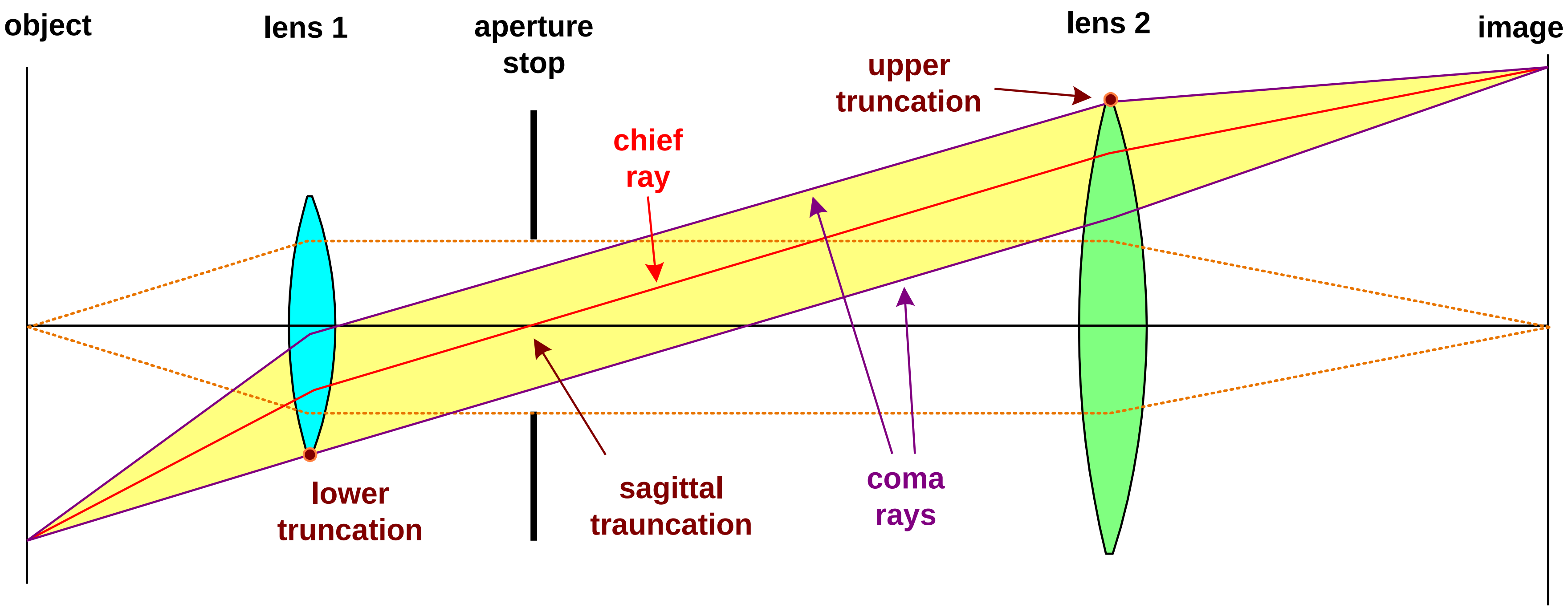
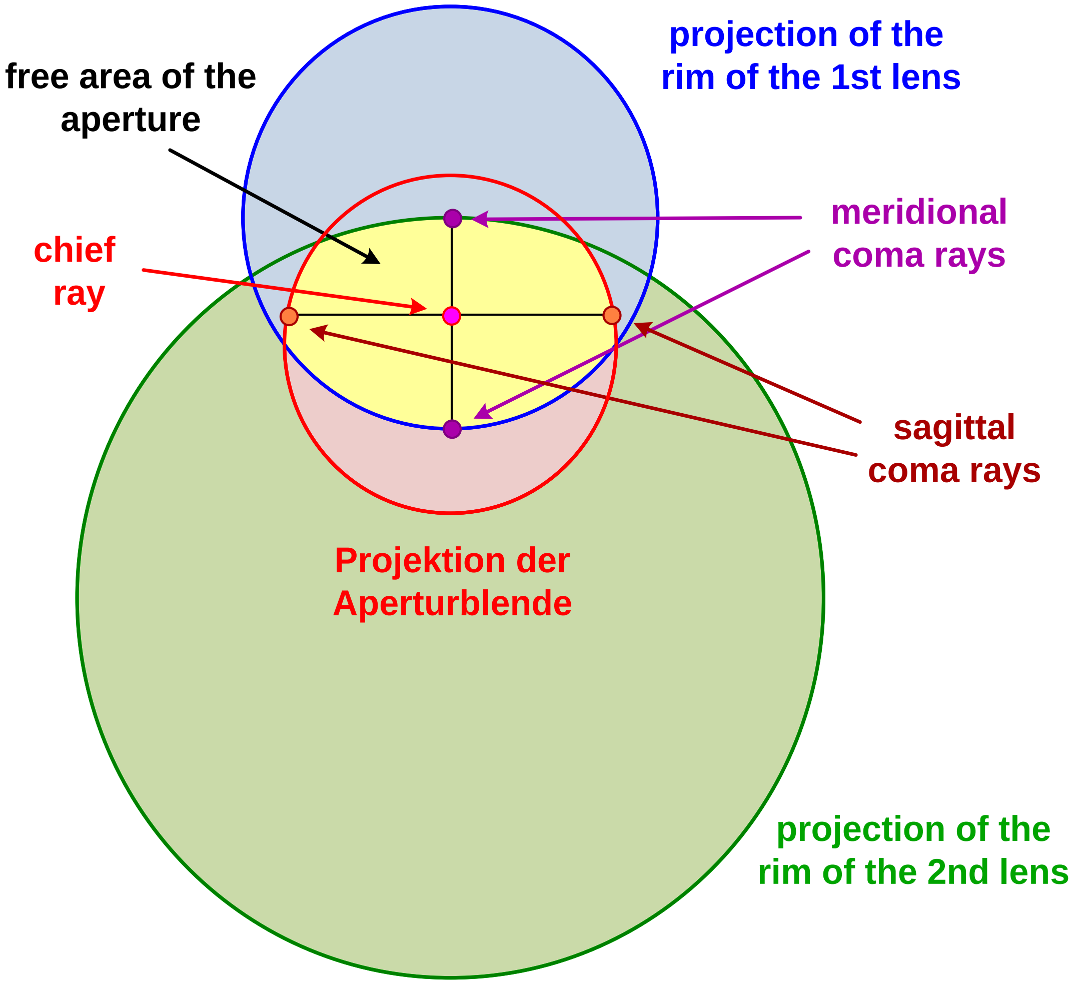
- 3D-effects due to vignetting
- Truncation of the at different surfaces for the upper and the lower part of the cone



Vignetting

- Truncation of the light cone with asymmetric ray path for off-axis field points
- Intensity decrease towards the edge of the image
- Definition of the chief ray: ray through energetic centroid
- Vignetting can be used to avoid uncorrectable coma aberrations in the outer field
- Effective free area with extrem aspect ratio: anamorphic resolution

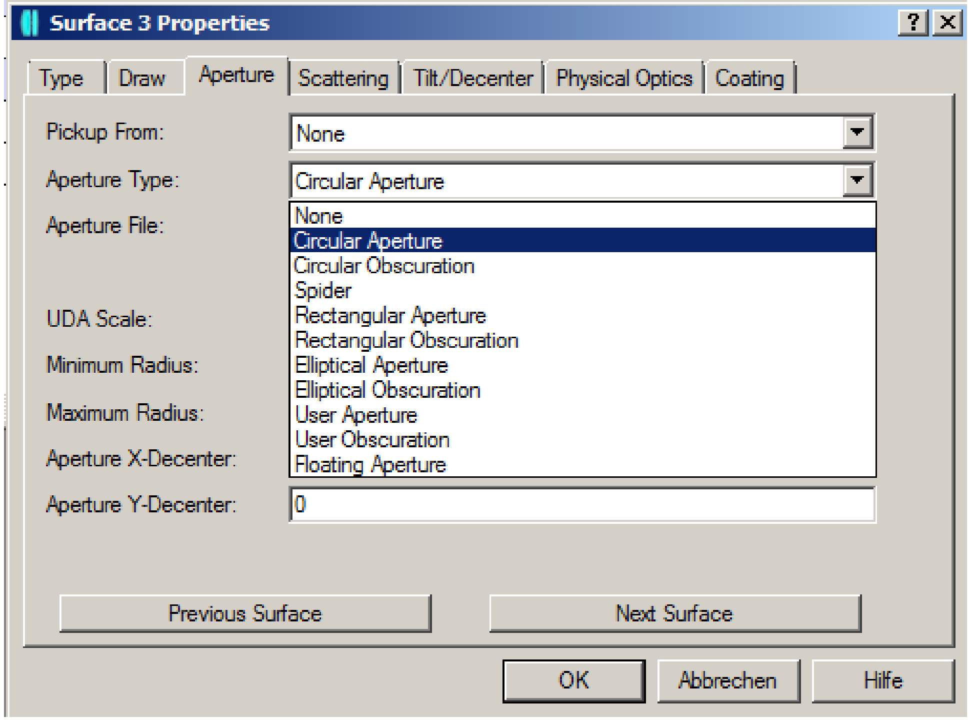


2 Properties of Optical Systems I
Diameters and stop sizes

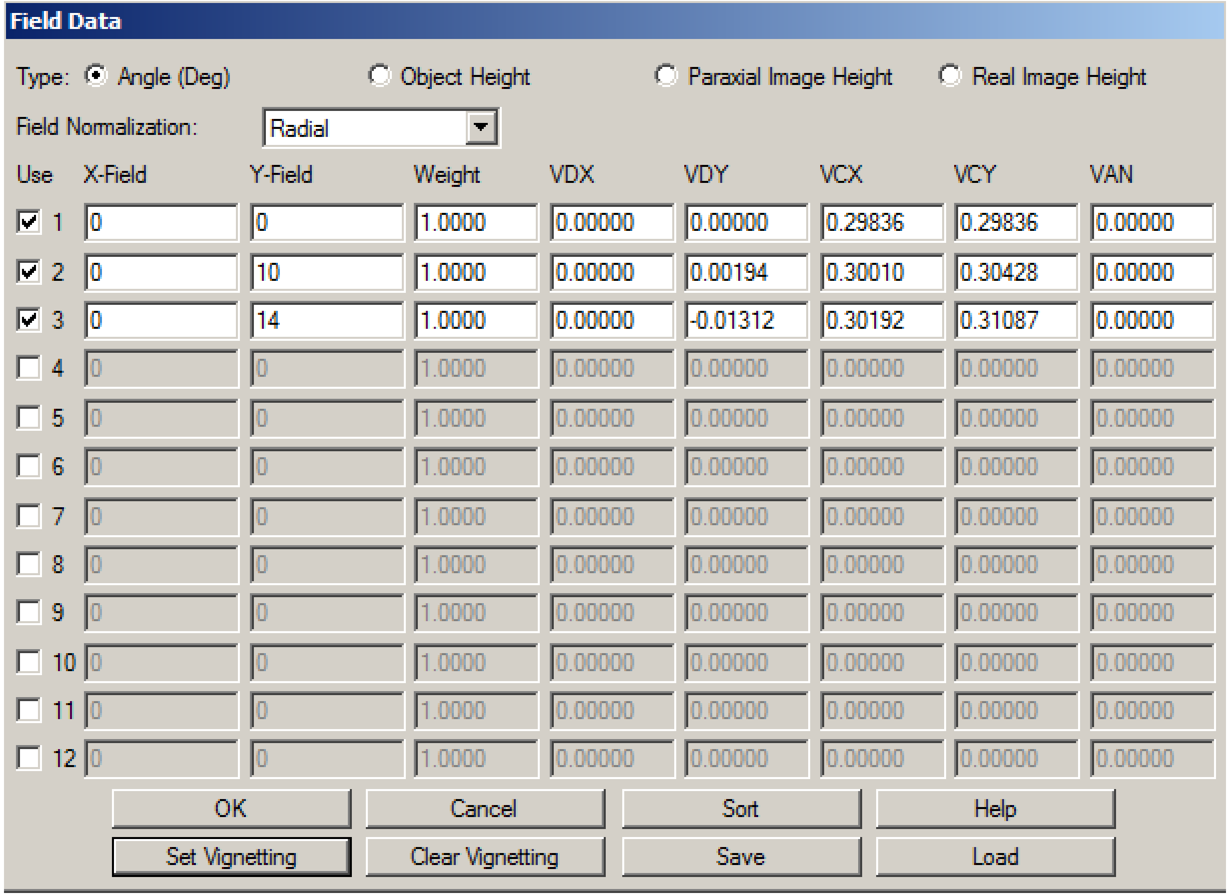
1. Determination of one surface as system stop:
   - Fixes the chief ray intersection point with axis
   - can be set in surface properties menu
   - indicated by STO in lens data editor
   - determines the aperture for the option 'float by stop size'

2. Diameters in lens data editor
   - indicated U for user defined
   - only circular shape
   - effects drawing
   - effects ray vignetting
   - can be used to draw 'nice lenses' with overflow of diameter

3. Diameters as surface properties:
   - effects on rays in drawing (vignetting)
   - no effect on lens shapes in drawing
   - also complicated shapes and decenter possible
   - indicated in lens data editor by a star



4. Individual aperture sizes for every field point can be set by the vignetting factors of the Field menu
   - real diameters at surfaces must be set
   - reduces light cones are drawn in the layout



Field Data

Type: (•) Angle (Deg) ( ) Object Height ( ) Paraxial Image Height ( ) Real Image Height

Field Normalization: Radial

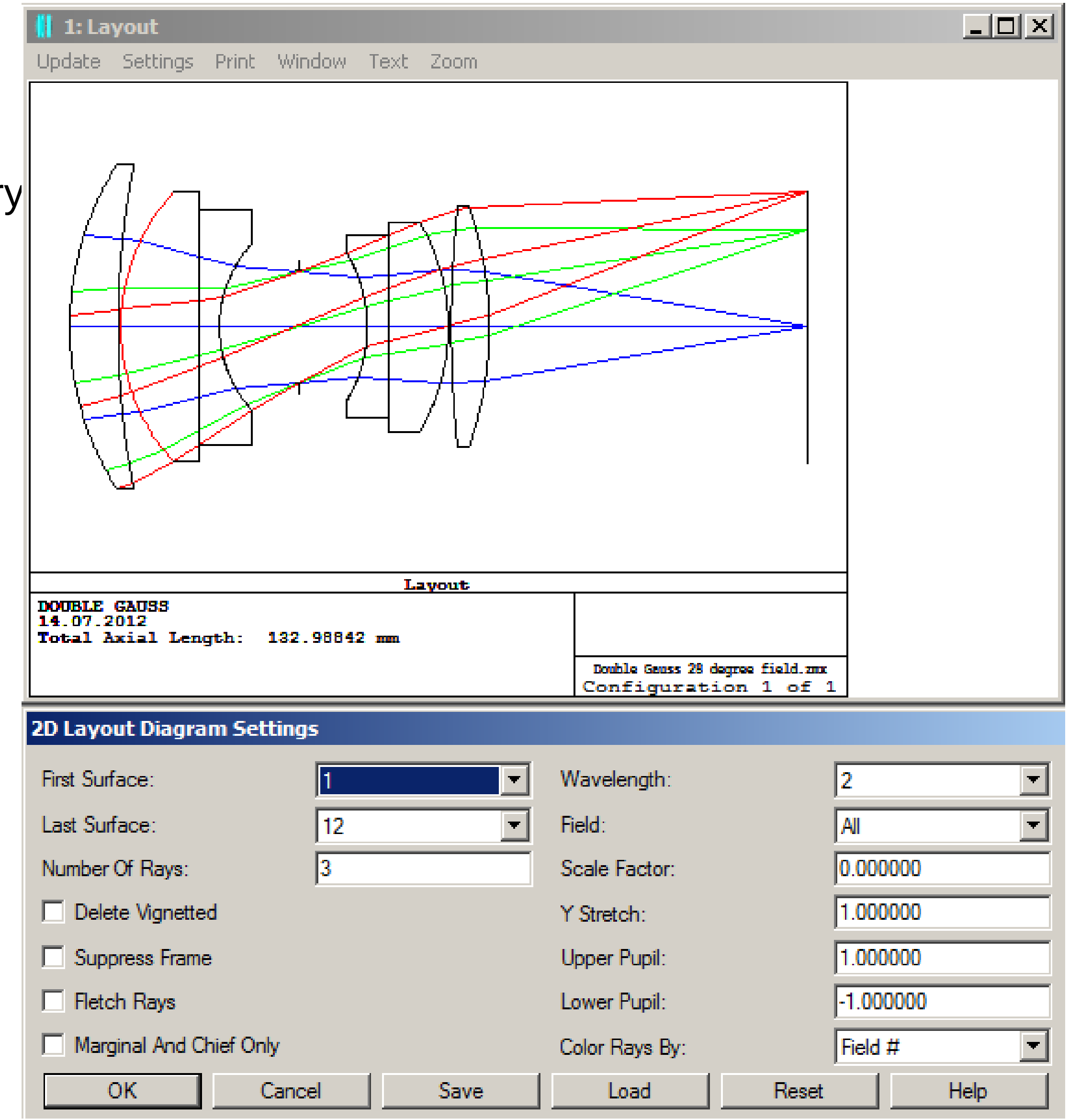
Use		X-Field	Y-Field	Weight	VDX	VDY	VCX	VCY	VAN
☑	1	0	0	1.0000	0.00000	0.00000	0.29836	0.29836	0.00000
☑	2	0	10	1.0000	0.00000	0.00194	0.30010	0.30428	0.00000
☑	3	0	14	1.0000	0.00000	-0.01312	0.30192	0.31087	0.00000
☐	4	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
☐	5	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
☐	6	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
☐	7	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
☐	8	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
☐	9	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
☐	10	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
☐	11	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
☐	12	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000

OK | Cancel | Sort | Help
Set Vignetting | Clear Vignetting | Save | Load

2 Properties of Optical Systems I
Layout options

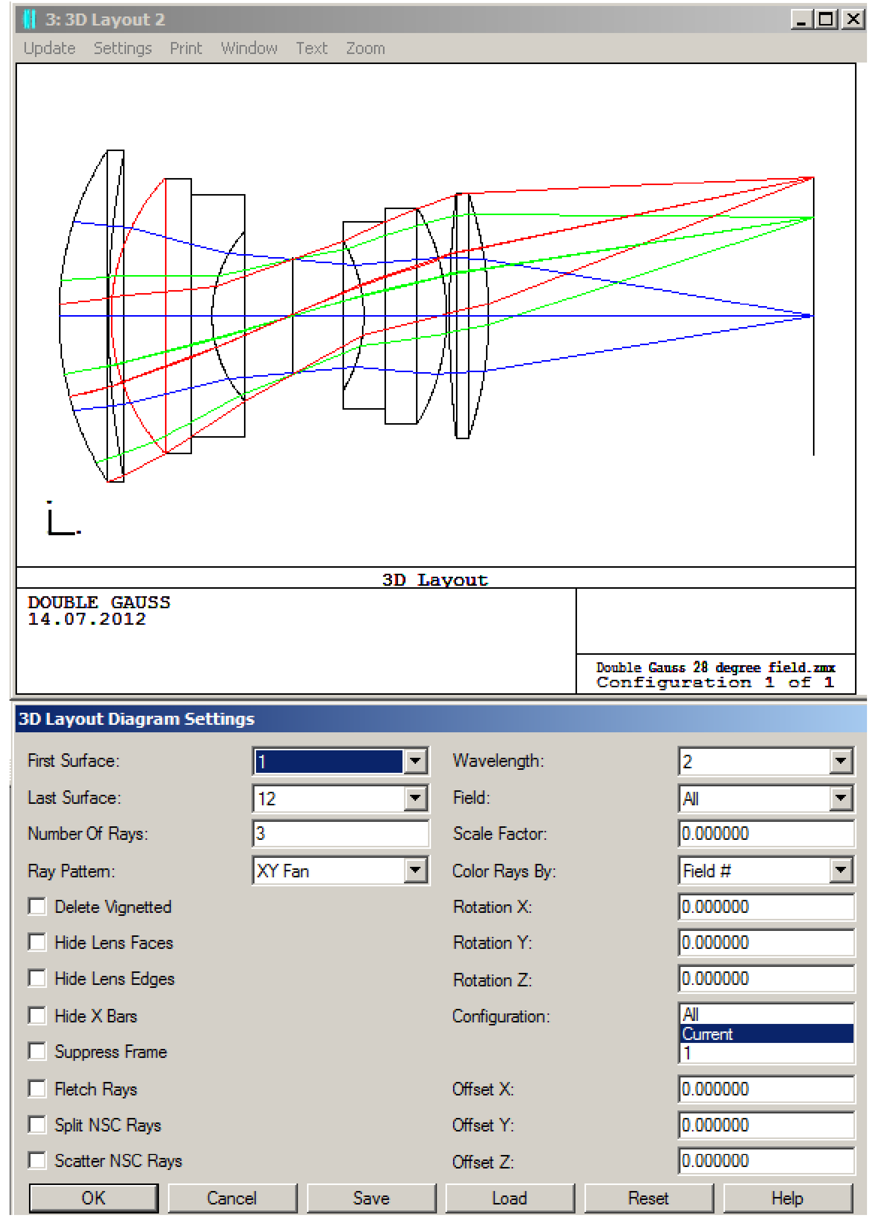
- Graphical control of system and ray path
- Principal options in Zemax:
  1. 2D section for circular symmetry
  2. 3D general drawing

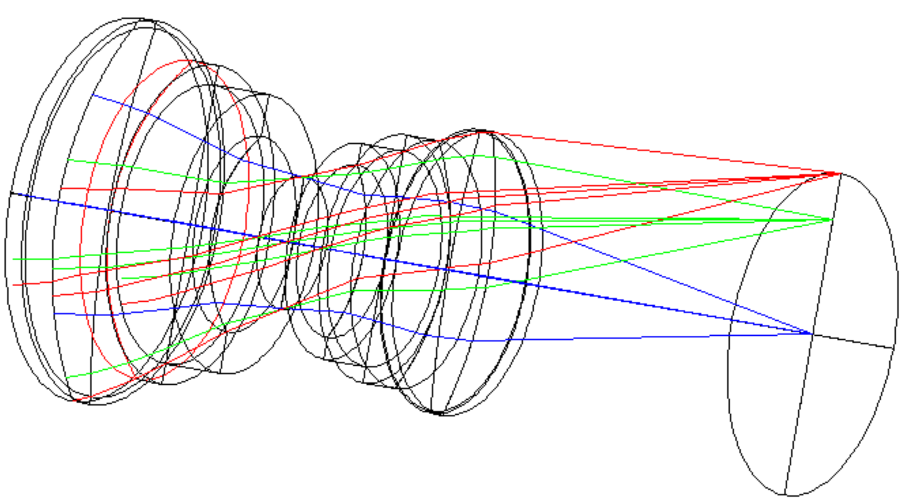
- Several options in settings
- Zooming with mouse



2 Properties of Optical Systems I
Layout options

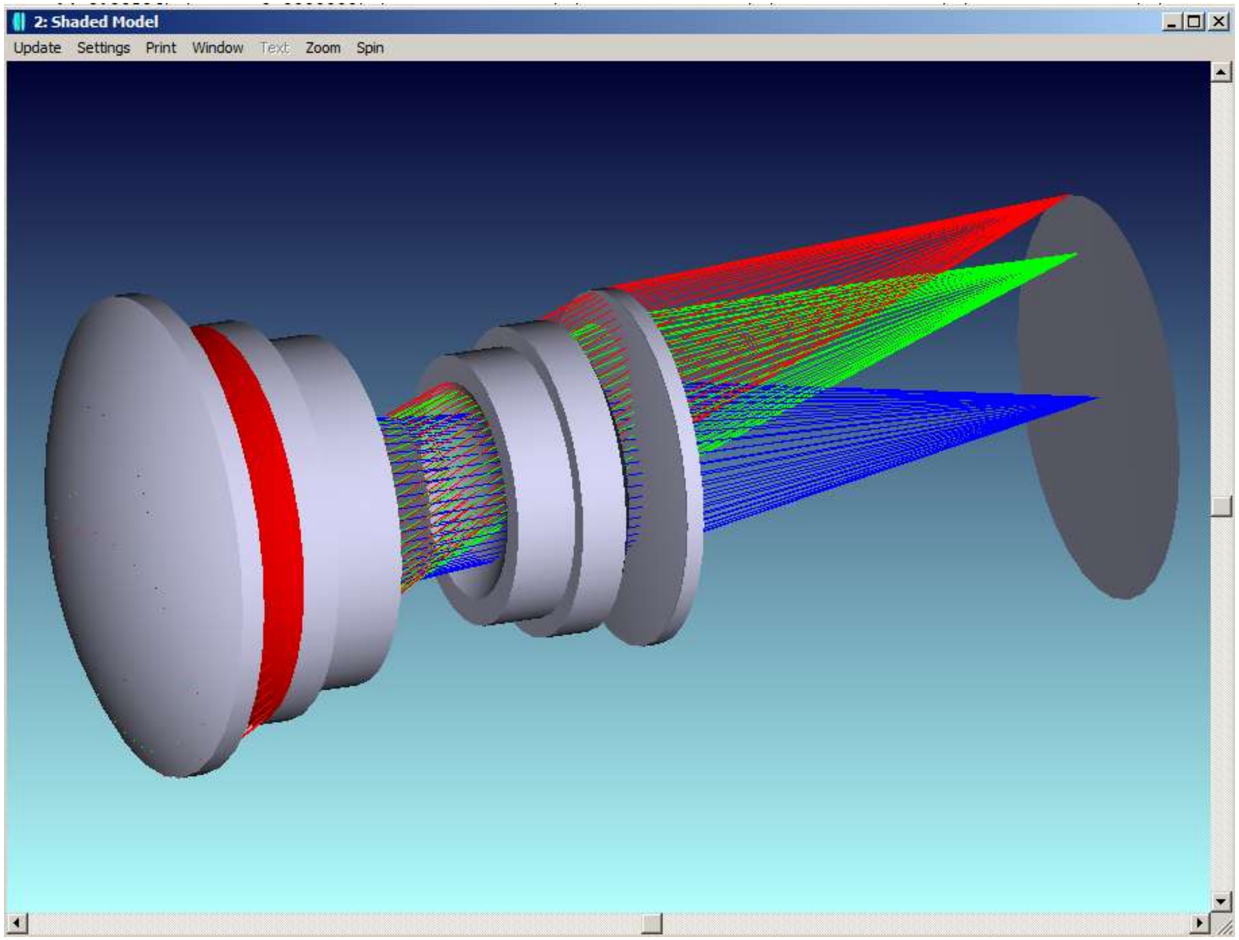
- Different options for 3D case
- Multiconfiguration plot possible
- Rayfan can be chosen





2 Properties of Optical Systems I
Layout options

- Professional graphic
- Many layout options
- Rotation with mouse or arrow buttons



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- Important types of optical materials:
  1. Glasses
  2. Crystals
  3. Liquids
  4. Plastics, cement
  5. Gases
  6. Metals

- Optical parameters for characterization of materials
  1. Refractive index, spectral resolved $n(\lambda)$
  2. Spectral transmission $T(\lambda)$
  3. Reflectivity R
  4. Absorption
  5. Anisotropy, index gradient, eigenfluorescence,…

- Important non-optical parameters
  1. Thermal expansion coefficient
  2. Hardness
  3. Chemical properties (resistence,…)

2 Properties of Optical Systems I
Test wavelengths

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λ in [nm]	Name	Color	Element
248.3		UV	Hg
280.4		UV	Hg
296.7278		UV	Hg
312.5663		UV	Hg
334.1478		UV	Hg
365.0146	i	UV	Hg
404.6561	h	violett	Hg
435.8343	g	blau	Hg
479.9914	F'	blau	Cd
486.1327	F	blau	H
546.0740	e	grün	Hg
587.5618	d	gelb	He
589.2938	D	gelb	Na
632.8			HeNe-Laser
643.8469	C'	rot	Cd
656.2725	C	rot	H
706.5188	r	rot	He
852.11	s	IR	Cä
1013.98	t	IR	Hg
1060.0			Nd:YAG-Laser

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- Description of dispersion:

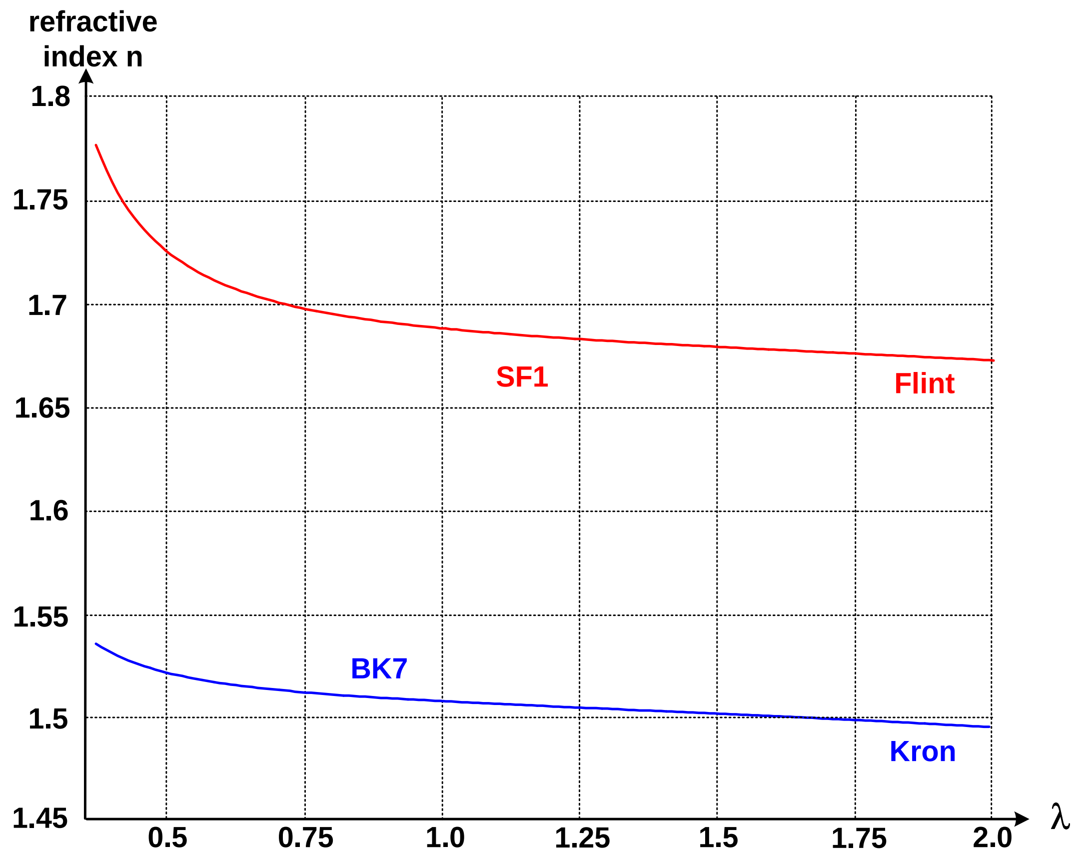
  Abbe number $$\nu(\lambda) = \frac{n(\lambda) - 1}{n_{F'} - n_{C'}}$$

- Visual range of wavelengths:

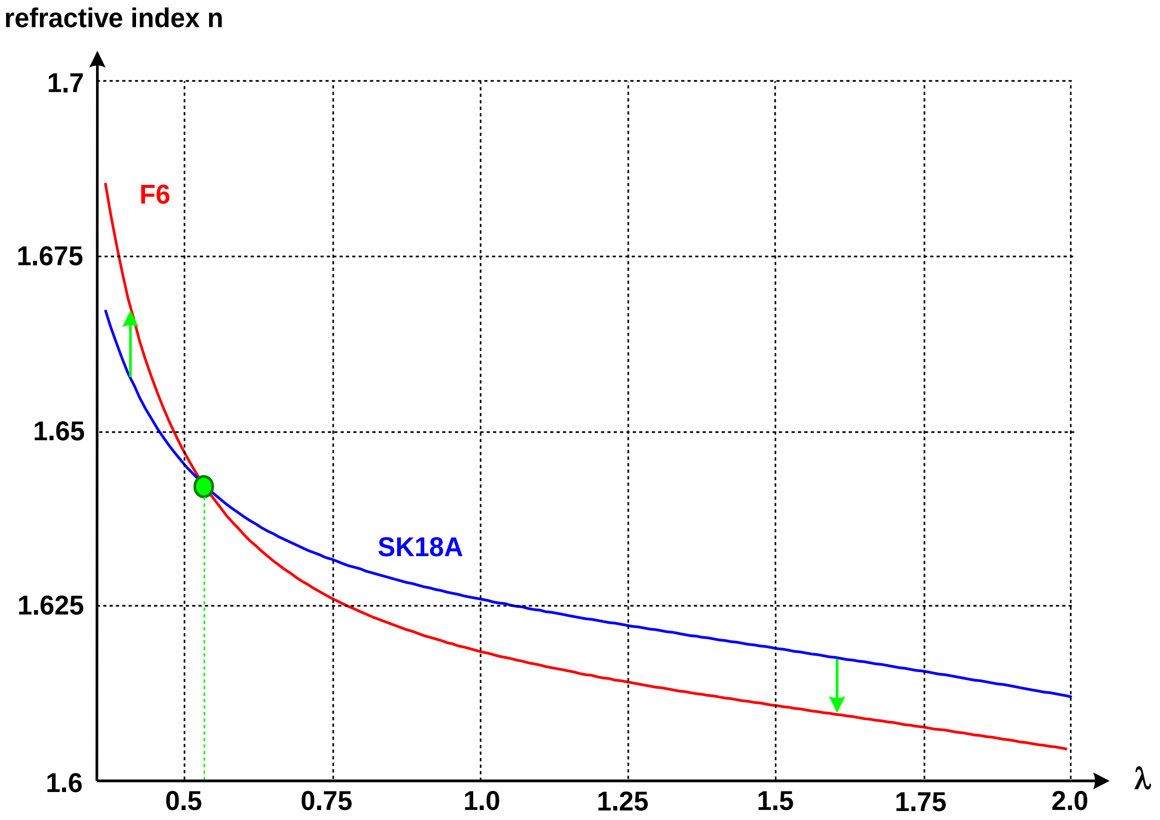
$$\nu_e = \frac{n_e - 1}{n_{F'} - n_{C'}}$$

- Typical range of glasses
  ν_e = 20 ...120

- Two fundamental types of glass:
  Crone glasses:
  n small, ν large
  Flint glasses
  n large, ν small



Material with different dispersion values:
- Different curvature of the dispersion curve
- Stronger change of index over wavelength for large dispersion
- Inversion of index sequence at the boundaries of the spectrum possible



- Schott formula
  empirical

$$n = \sqrt{a_o + a_1\lambda^2 + a_2\lambda^{-2} + a_3\lambda^{-4} + a_4\lambda^{-6} + a_5\lambda^{-8}}$$

- Sellmeier
  Based on oscillator model

$$n(\lambda) = \sqrt{A + B\frac{\lambda^2}{\lambda^2 - \lambda_1^2} + C\frac{\lambda^2}{\lambda^2 - \lambda_2^2}}$$

- Bausch-Lomb
  empirical

$$n(\lambda) = \sqrt{A + B\lambda^2 + C\lambda^4 + \frac{D}{\lambda^2} + \frac{E\lambda^2}{(\lambda^2 - \lambda_o^2) + \frac{F\lambda^2}{\lambda^2 - \lambda_o^2}}}$$

- Herzberger
  Based on oscillator model

$$n(\lambda) = a_o + a_1\lambda^2 + \frac{a_2}{\lambda^2 - \lambda_o^2} + \frac{a_3}{\left(\lambda^2 - \lambda_o^2\right)^2}$$

$$mit \quad \lambda_o = 0.168\ \mu m$$

- Hartmann
  Based on oscillator model

$$n(\lambda) = a_o + \frac{a_1}{a_3 - \lambda} + \frac{a_4}{a_5 - \lambda}$$

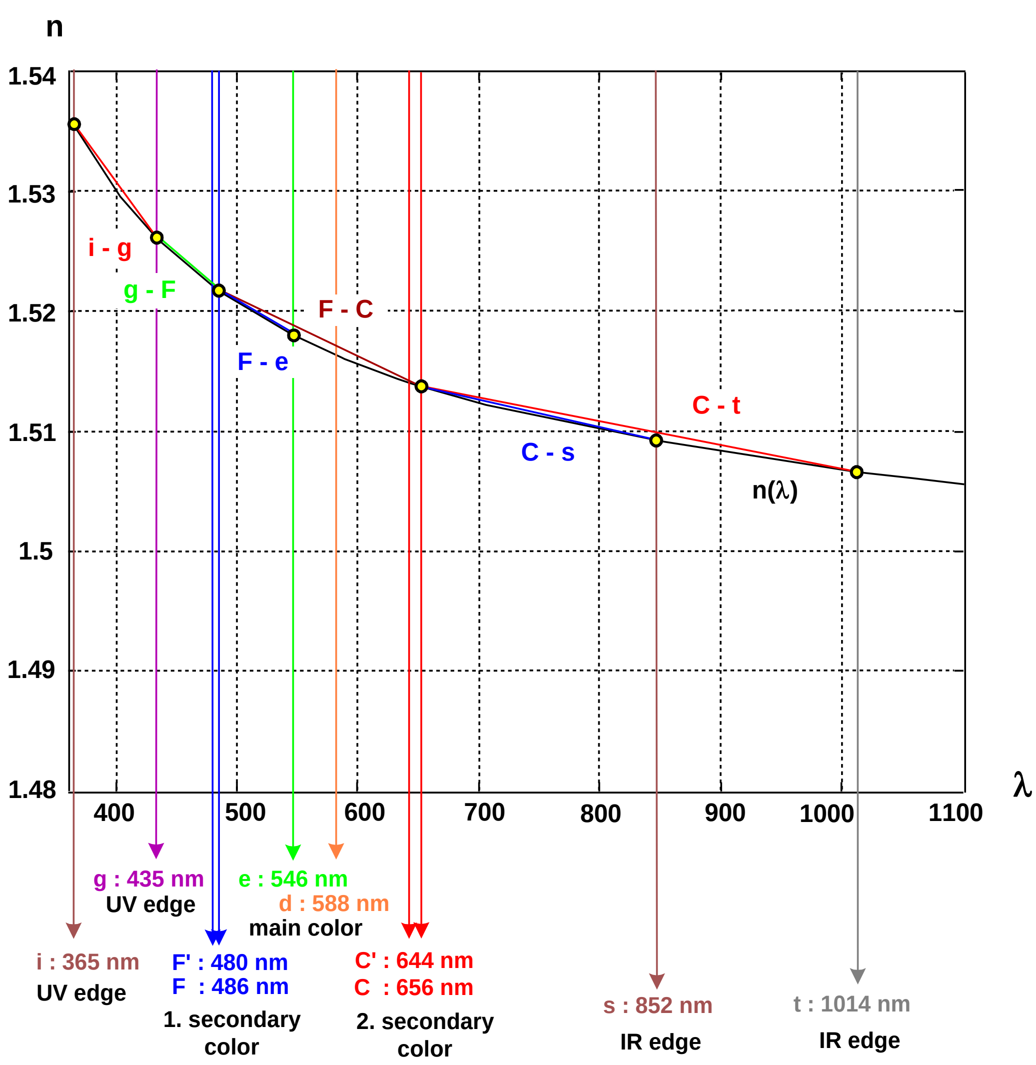
Relative partial dispersion

- Relative partial dispersion :
  Change of dispersion slope with λ
- Definition of local slope for selected wavelengths relative to secondary colors

$$P_{\lambda_1\lambda_2} = \frac{n(\lambda_1) - n(\lambda_2)}{n_{F'} - n_{C'}}$$

- Special selections for characteristic ranges of the visible spectrum

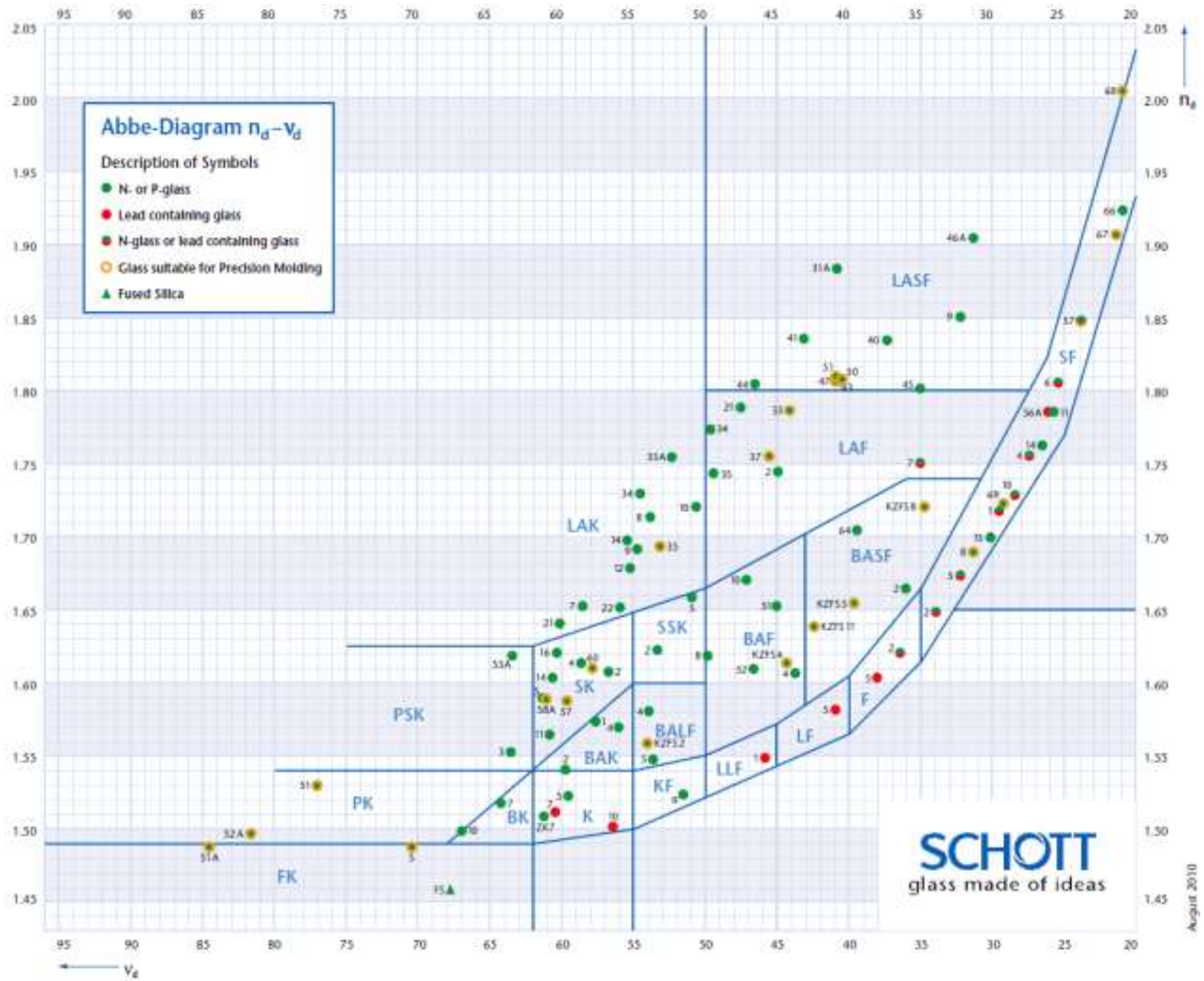
λ = 656 / 1014 nm far IR
λ = 656 / 852 nm near IR
λ = 486 / 546 nm blue edge of VIS
λ = 435 / 486 nm near UV
λ = 365 / 435 nm far UV



Glass diagram

- Usual representation of glasses:
  diagram of refractive index vs dispersion n(ν)

- Left to right:
  Increasing dispersion
  decreasing Abbe number



Glass:
LAFN7

Part 1

Main data		Refractive indices			Internal transmission data			relative partial dispersion		Anomalous partial dispersion	
			λ [nm]	n	λ [nm]	τ_i [10 mm]	τ_i [25 mm]				
LAFN7	750350.438	n2325,4	2325,4	1,70211	2500,0	0,380	0,090	Ps,t	0,2360	ΔPc,t	0,0174
n_d	1,74950	n1970,1	1970,1	1,70934	2325,4	0,700	0,410	PC,s	0,4921	ΔPc,s	0,0078
n_e	1,75458	n1529,6	1529,6	1,71726	1970,1	0,940	0,850	Pd,C	0,2941	ΔPF,e	-0,0011
ν_d	34,95	n1060,0	1060,0	1,72642	1529,6	0,984	0,960	Pe,d	0,2369	ΔPg,F	-0,0025
ν_e	34,72	nt	1014,0	1,72758	1060,0	0,998	0,996	Pg,F	0,5825	ΔPi,g	-0,0093
n_F-n_C	0,02145	ns	852,1	1,73264	700,0	0,998	0,996	Pi,h	0,9160		
$n_{F'}-n_{C'}$	0,021735	nr	706,5	1,73970	660,0	0,998	0,995				
		nC	656,3	1,74319	620,0	0,998	0,995	P's,t	0,2329		
		nC'	643,8	1,74418	580,0	0,998	0,995	P'C',s	0,5311		
		n632,8	632,8	1,74511	546,1	0,998	0,994	P'd,C'	0,2446		
		nD	589,3	1,74931	500,0	0,998	0,994	P'e,d	0,2338		
		nd	587,6	1,74950	460,0	0,993	0,982	P'g,F'	0,5158		
		ne	546,1	1,75458	435,8	0,986	0,965	P'i,h	0,9037		
		nF	486,1	1,76464	420,0	0,976	0,940				
		nF'	480,0	1,76592	404,7	0,950	0,880				
		ng	435,8	1,77713	400,0	0,940	0,850				
		nh	404,7	1,78798	390,0	0,910	0,780				
		ni	365,0	1,80762	380,0	0,840	0,650				
		n334,1	334,1	0,00000	370,0	0,690	0,400				
		n312,6	312,6	0,00000	365,0	0,550	0,220				
		n296,7	296,7	0,00000	350,0	0,130	0,010				
		n280,4	280,4	0,00000	334,1	0,000	0,000				
		n248,3	248,3	0,00000	320,0	0,000	0,000				
					310,0	0,000	0,000				

Glass:
LAFN7

Part 2

Sellmeier dispersion constants		Constants of dn/dT		Other properties		Temperature coefficients						
							dn rel / dT [10 -6/K]			dn abs / dT [10-6/K]		
B_1	1,66842615E+00	D_0	7,27E-06	$\alpha_{-30/+70°C}$ [10^{-6}/K]	5,3	[°C]	1060,0	e	g	1060,0	e	g
B_2	2,98512803E -01	D_1	1,31E-08	$\alpha_{+20/+300°C}$ [10^{-6}/K]	6,4	-40/ -20	6,00	7,80	9,70	3,70	5,40	7,20
B_3	1,07743760E+00	D_2	-3,32E-11	Tg[°C]	500	+20/+40	6,30	8,30	10,40	4,80	6,70	8,90
C_1	1,03159999E -02	E_0	8,88E-07	T10 13,0[°C]	481	+60/+80	6,50	8,60	10,90	5,30	7,40	9,70
C_2	4,69216348E -02	E_1	9,32E-10	T10 7,6[°C]	573							
C_3	8,25078509E+01	λ_{TK} [µm]	2,48E-01	c_p [J/(g·K)]	0,000							
				λ [W/(m·K)]	0,770							
				ρ [g/cm^3]	4,38							
				E[10^3 N/mm^2]	80							
				µ	0,280							
				K[10^{-6} mm^2/N]	1,77							
				HK0,1/20	520							
				HG	3							
				B	0							
				CR	3							
				FR	1							
				SR	53							
				AR	2,2							
				PR	4,3							

Ranges of glass map

Crown glasses

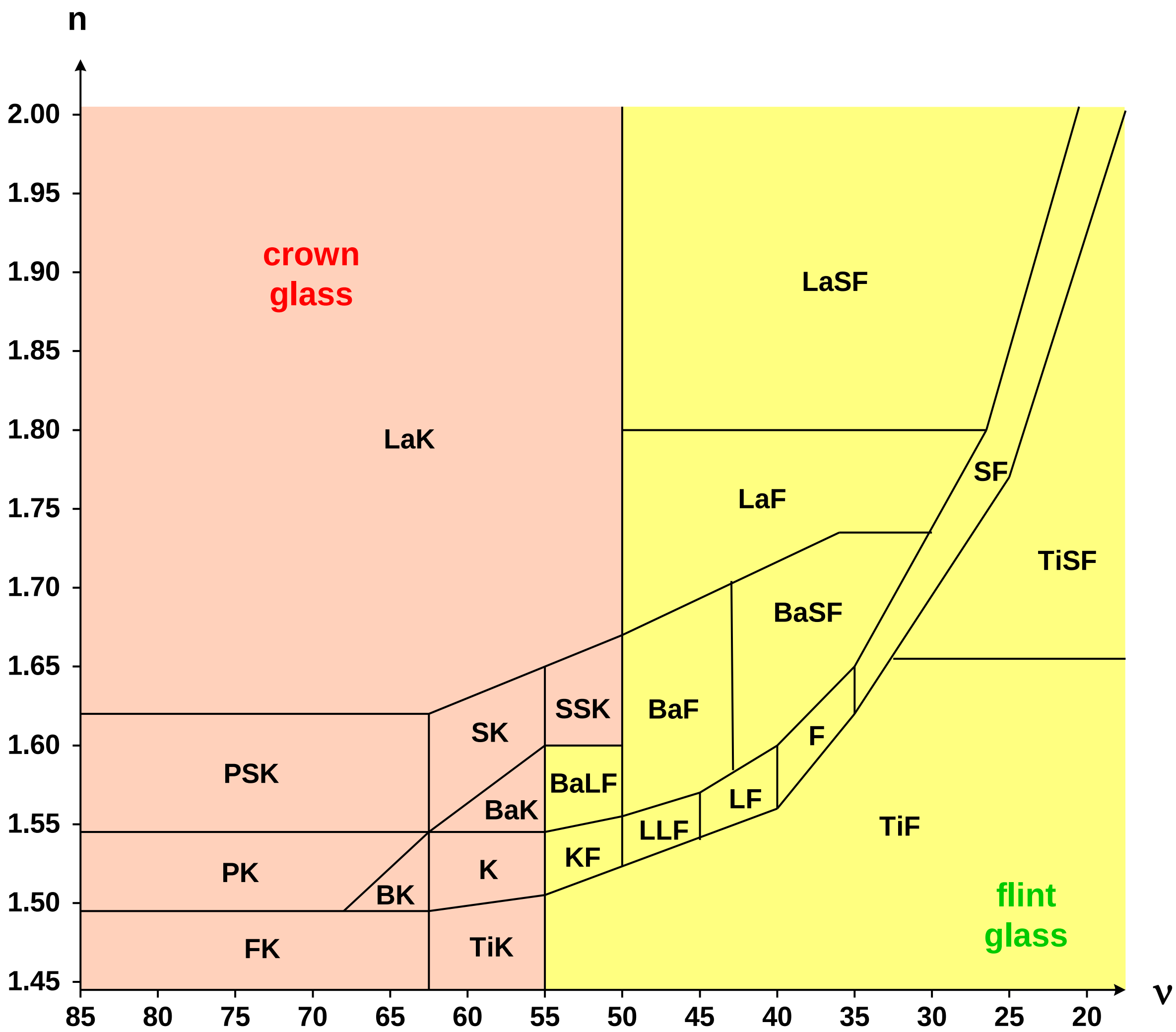
$$\nu_e > 54.7 \qquad f\ddot{u}r \quad n_e < 1.6028$$

$$\nu_e > 49.7 \qquad f\ddot{u}r \quad n_e > 1.6028$$

Flint glasses

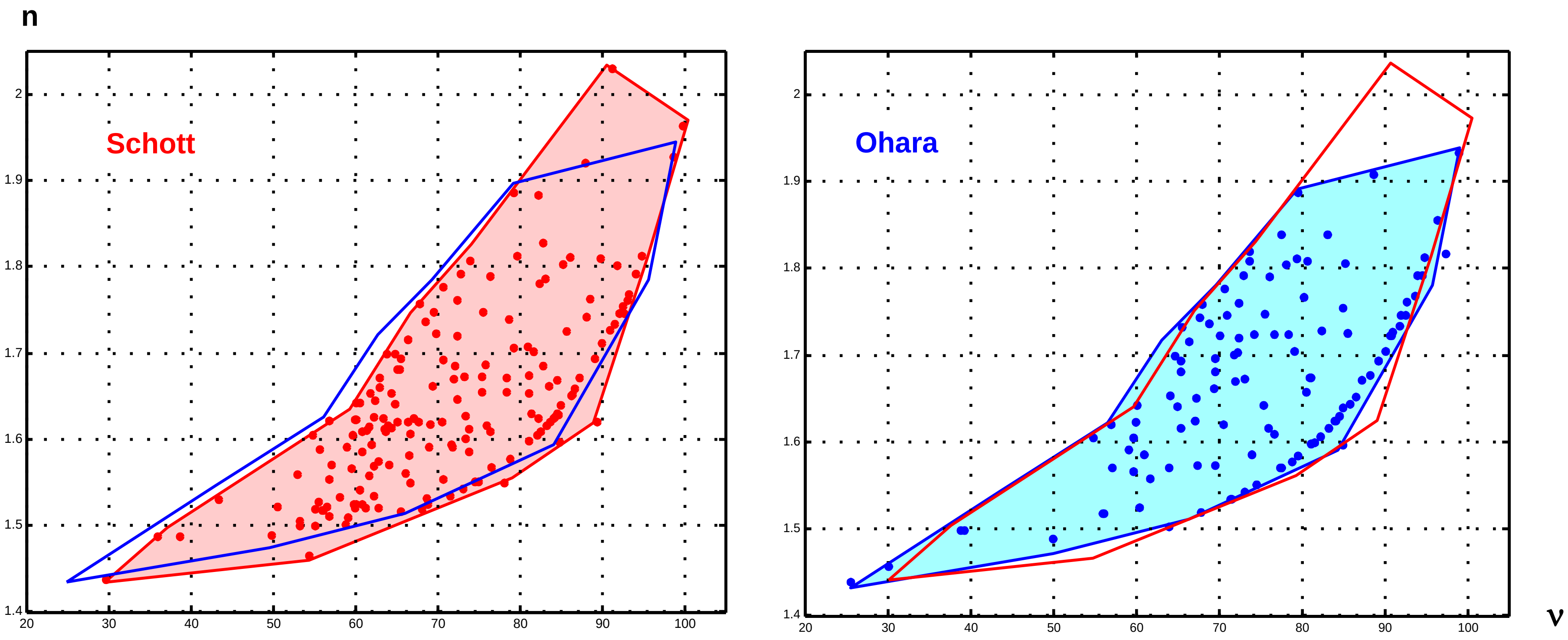
$$\nu_e < 54.7 \qquad f\ddot{u}r \quad n_e < 1.6028$$

$$\nu_e < 49.7 \qquad f\ddot{u}r \quad n_e > 1.6028$$



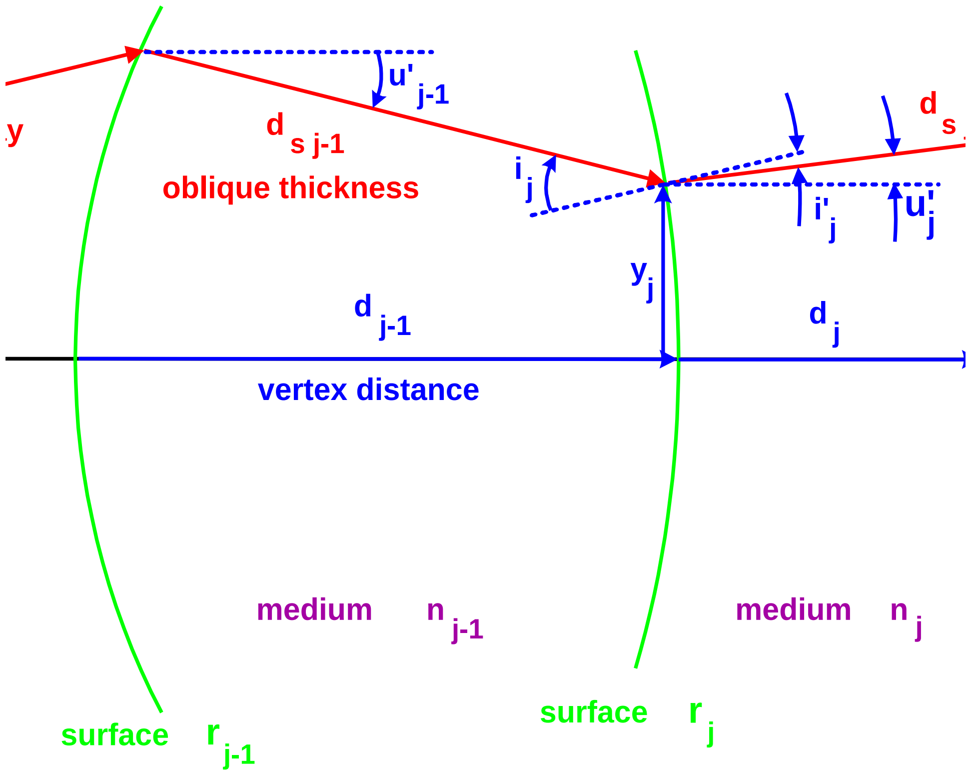
2 Properties of Optical Systems I
Ranges of glass map - availability

- Nearly equal area in the glass diagramm with available materials for all vendors
- No options with Index / dispersion
  1. high / high
  2. low / low

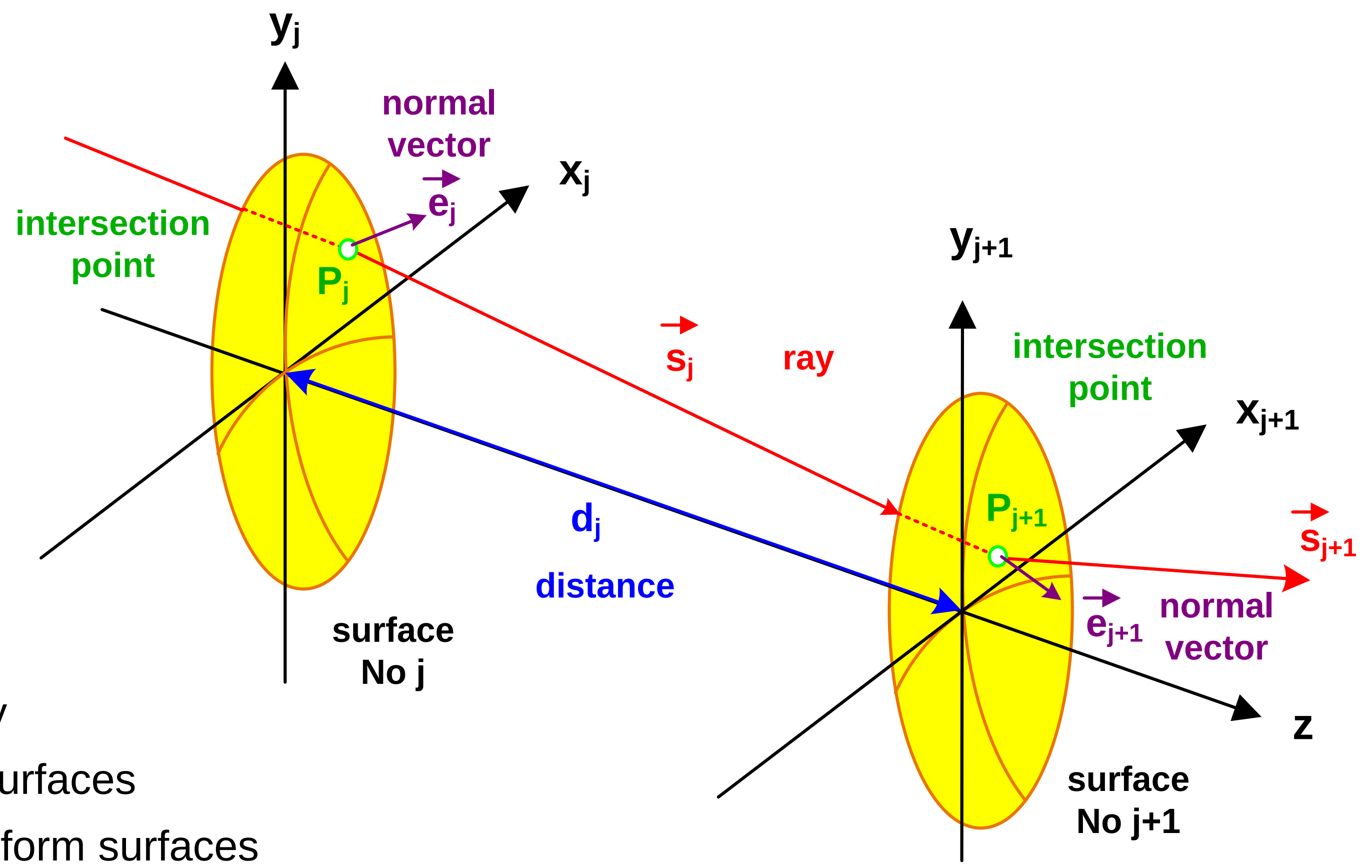


Scheme of raytrace

- Ray: straight line between two intersection points
- System: sequence of spherical surfaces
- Data: - radii, curvature c=1/r
  - vertex distances
  - refractive indices
  - transverse diameter
- Surfaces of 2nd order:
  Calculation of intersection points analytically possible: fast computation



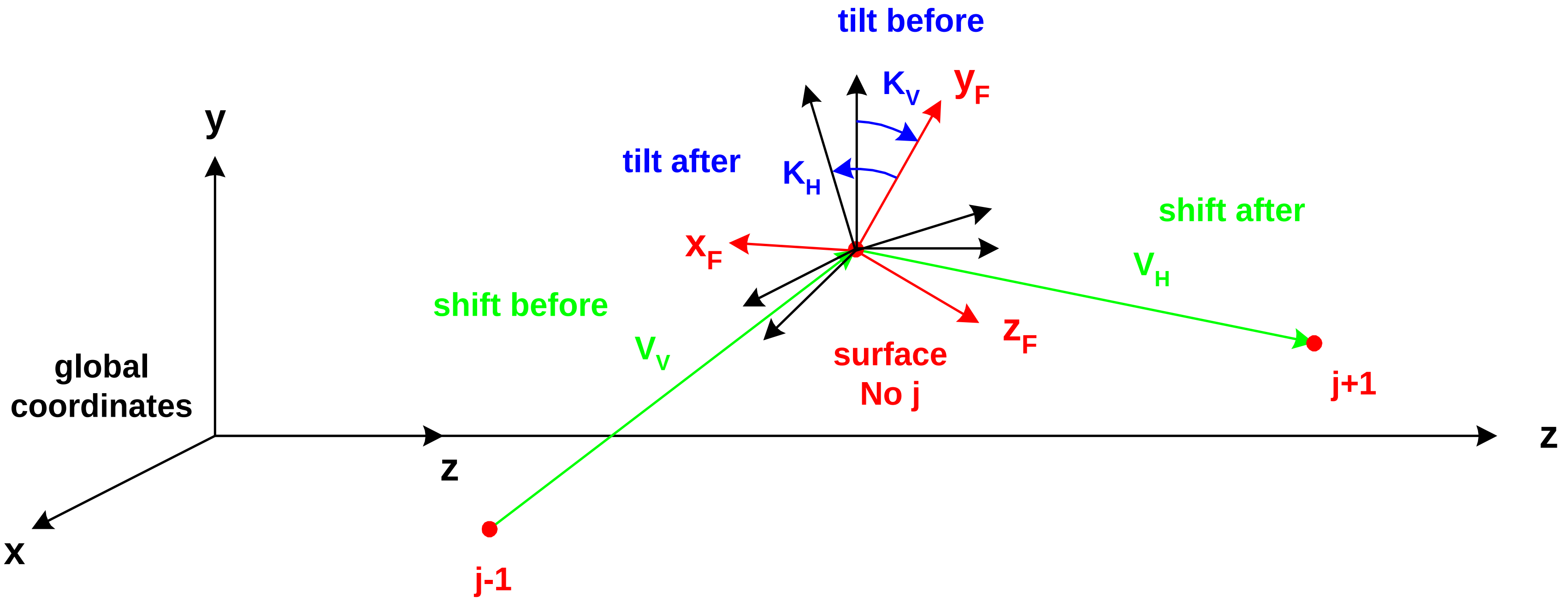
2 Properties of Optical Systems I
Vectorial raytrace



- General 3D geometry
- Tilt and decenter of surfaces
- General shaped free form surfaces
- Full description with 3 components
- Global and local coordinate systems

- Single surface:
  - tilt and decenter before refraction
  - decenter and tilt after refraction
- General setup for position and orientation in 3D

$$\vec{r}\,' = \underline{D}_H \cdot \underline{R}_H \cdot \underline{F} \cdot \underline{R}_V \cdot \underline{D}_V \cdot \vec{r}$$



Vectorial raytrace formulas

- Restrictions:
  - surfaces of second order, fast analytical calculation of intersection point possible
  - homogeneous media

- Direction unit vector of the straight ray

$$\vec{s}_j = \begin{pmatrix} \xi_j \\ \eta_j \\ \varsigma_j \end{pmatrix}$$

- Vector of intersection point on a surface

$$\vec{r}_j = \begin{pmatrix} x_j \\ y_j \\ z_j \end{pmatrix}$$

- Ray equation with skew thickness d_{sj}
  index j of the surface and the space behind

$$\vec{r}_j = \vec{r}_{j-1} + d_{s,j-1} \cdot \vec{s}_{j-1}$$

- Equation of the surface 2.order
  The coefficients H, F, G contains the surface shape parameters

$$H_j d_{s,j-1}^2 + 2F_j d_{s,j-1} - G_j = 0$$

2 Properties of Optical Systems I
Vectorial raytrace formulas

- Special case spherical surface with
  curvature c = 1/R
  Coefficients H, G, F

$$H_j = -c_j$$

$$G_j = c_j\left(x_j^2 + y_j^2 + z_j^2\right) - 2z_j$$

$$F_j = \varsigma_j - c_j\left(x_j\xi_j + y_j\eta_j + z_j\varsigma_j\right)$$

  Unit vector normal to the surface

$$\vec{e}_j = \begin{pmatrix} -c_j x_j \\ -c_j y_j \\ 1 - c_j z_j \end{pmatrix}$$

- Insertion of the ray equation into surface equation:
  skew thickness

$$d_{s,j-1} = \frac{G_j}{F_j + \sqrt{F_j^2 + H_j G_j}}$$

- Angle of incidence

$$\cos i_j = \vec{s}_j \cdot \vec{e}_j$$

- Refraction
  or
  reflection

$$\cos i'_j = \sqrt{1 - \left(\frac{n_j}{n_{j+1}}\right)^2 \left(1 - \cos^2 i_j\right)}$$

$$\cos i'_j = -\cos i_j$$

2 Properties of Optical Systems I
Vectorial raytrace formulas

- Auxiliary parameter

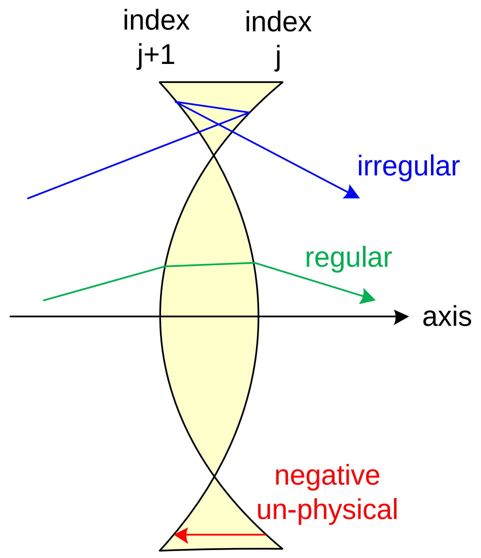
$$\Phi_j = n_{j+1} \cos i'_j - n_j \cos i_j$$

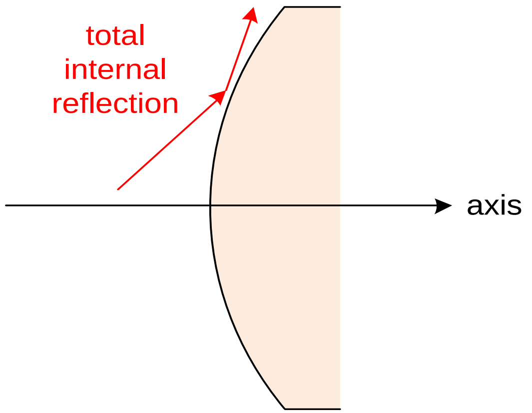
- New ray direction vector

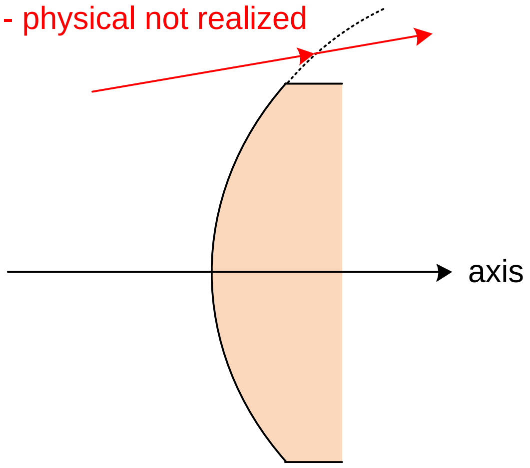
$$\vec{s}_{j+1} = \frac{n_j}{n_{j+1}} \vec{s}_j + \frac{\Phi_j}{n_{j+1}} \vec{e}_j$$

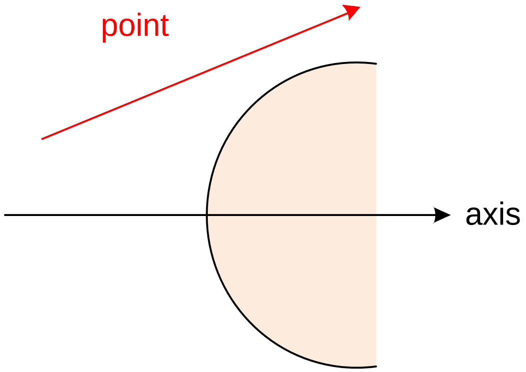
2 Properties of Optical Systems I
Raytrace errors

- Vignetting/truncation of ray at finite sized diameter:
  can or can not considered (optional)
- No physical intersection point of ray with surface
- Total internal reflection
- Negative edge thickness of lenses
- Negative thickness without mirror-reflection
- Diffraction at boundaries



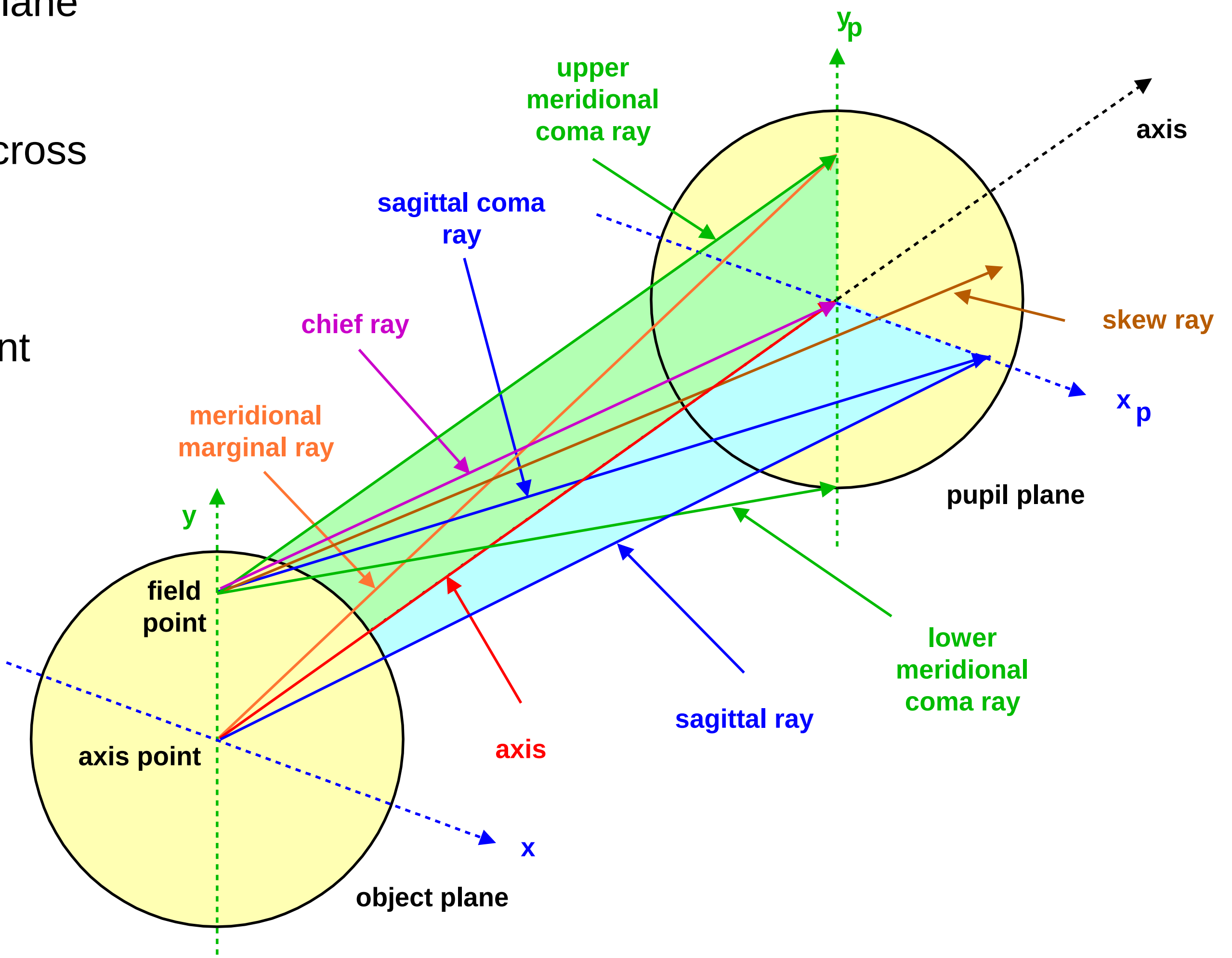






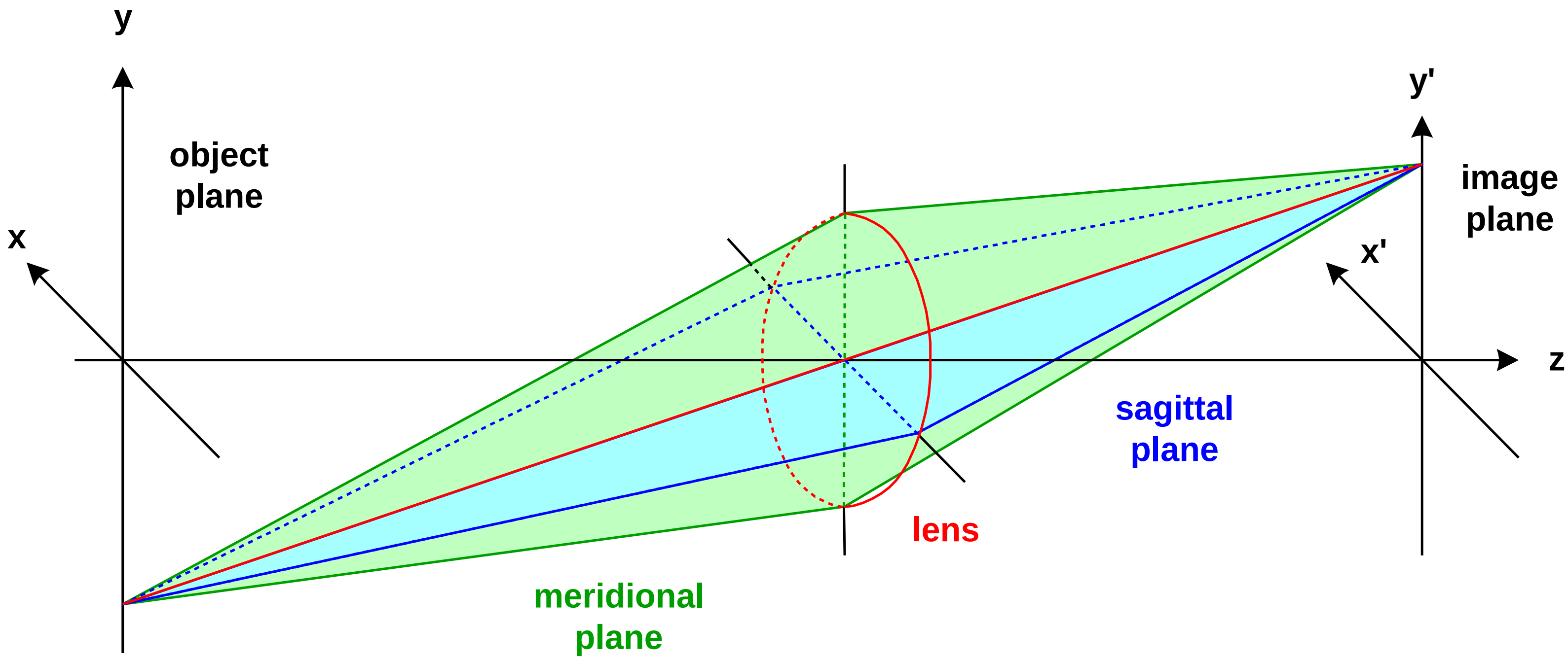
Special rays in 3D

- Meridional rays:
  in main cross section plane
- Sagittal rays:
  perpendicular to main cross section plane
- Coma rays:
  Going through field point and edge of pupil
- Oblique rays:
  without symmetry



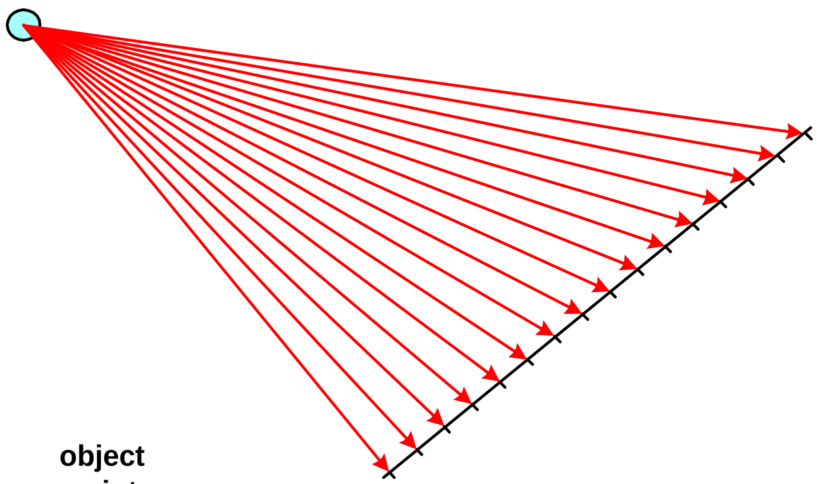
2 Properties of Optical Systems I
Tangential and sagittal plane

- Off-axis object point:
  1. Meridional plane / tangential plane / main cross section plane
     contains object point and optical axis
  2. Sagittal plane:
     perpendicular to meridional plane through object point

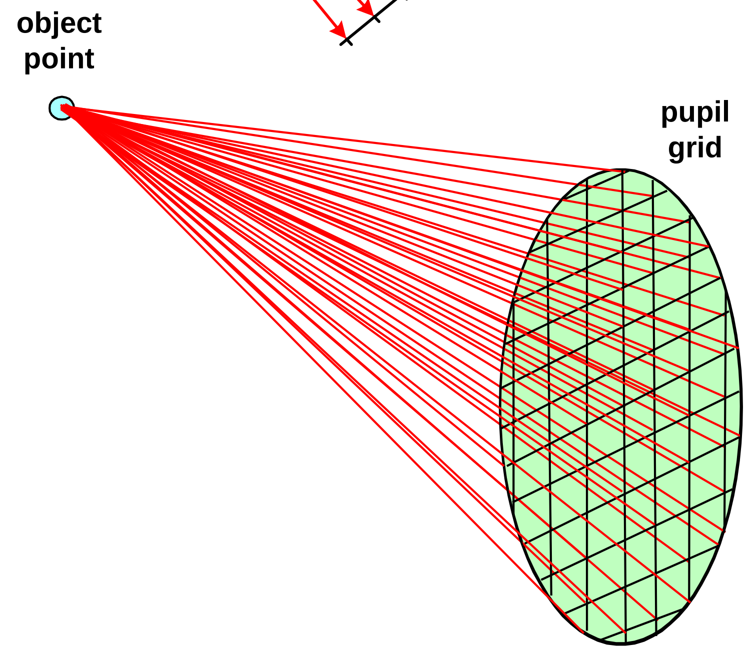


2 Properties of Optical Systems I
Ray fans and ray cones

- Ray fan:
  2-dimensional plane set of rays

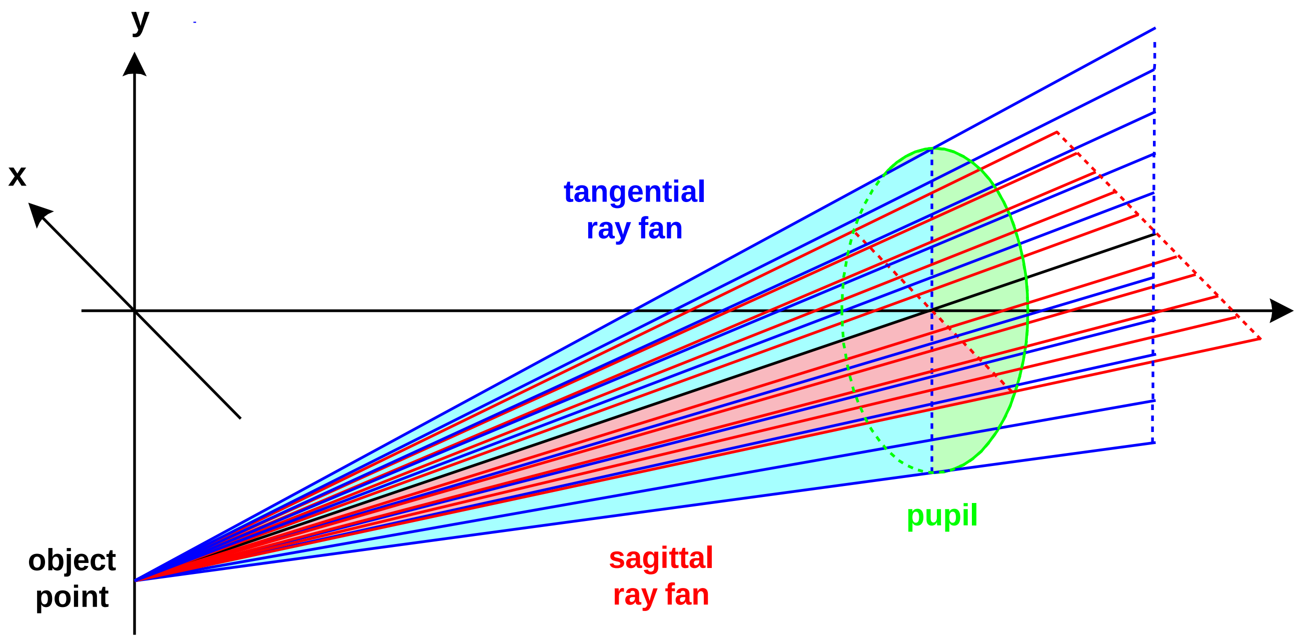


- Ray cone:
  3-dimensional filled ray cone



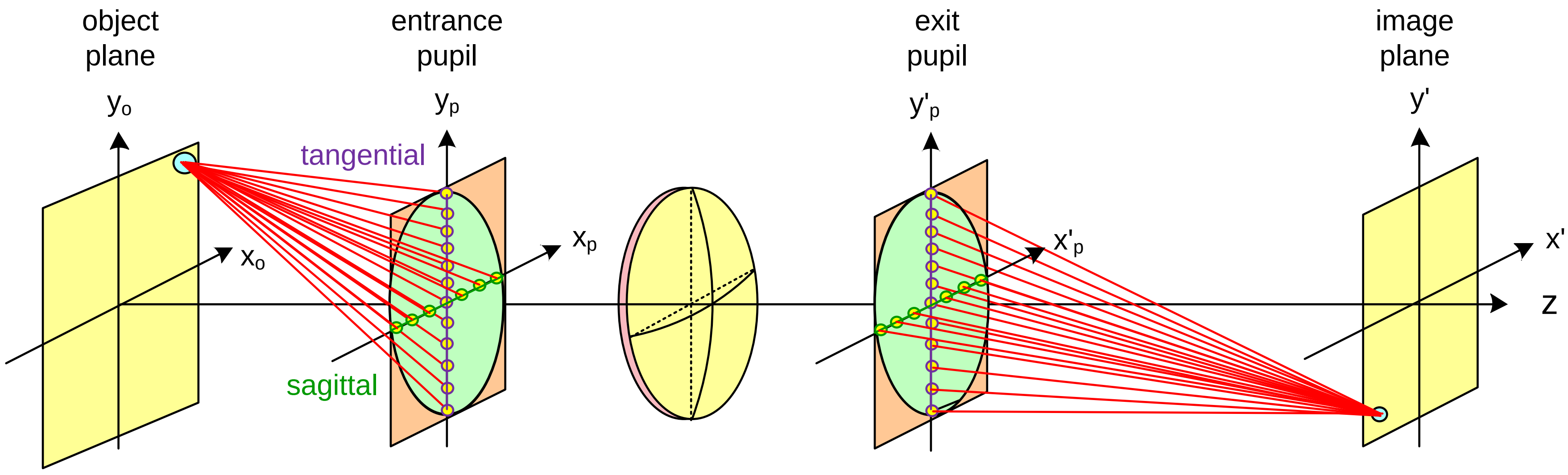
Ray fan selection for transverse aberrations plots

- Transverse aberrations:
  Ray deviation form ideal image point in meridional and sagittal plane respectively
- The sampling of the pupil is only filled in two perpendicular directions along the axes
- No information on the performance of rays in the quadrants of the pupil



Pupil sampling

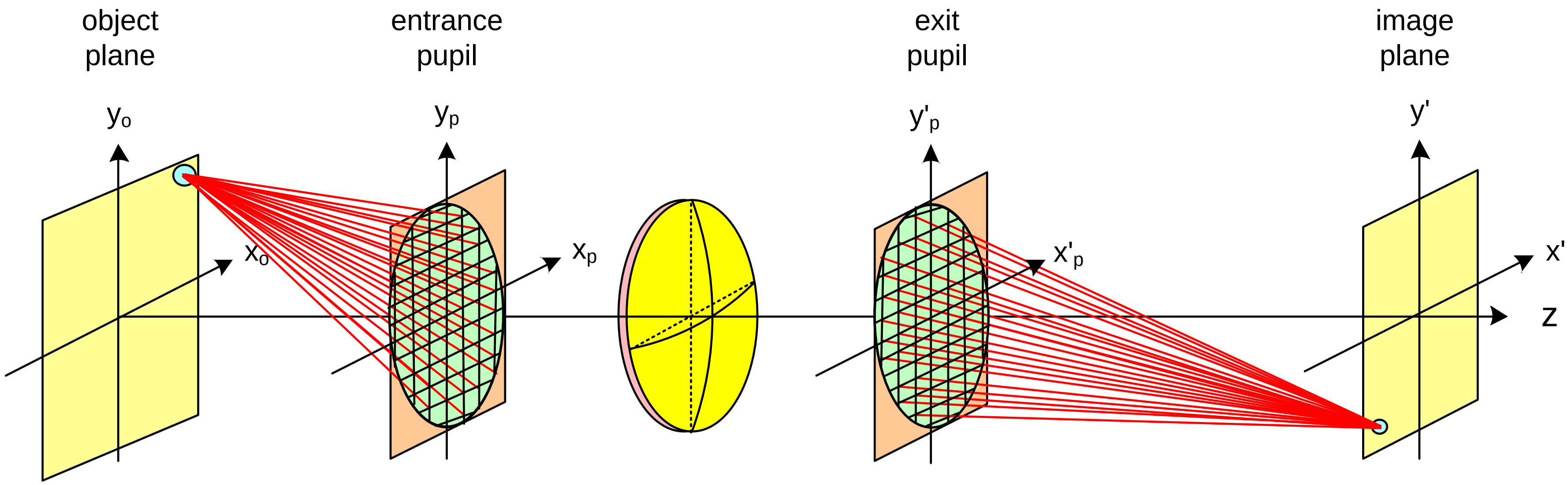
- Pupil sampling for calculation of transverse aberrations:
  all rays from one object point to all pupil points on x- and y-axis
- Two planes with 1-dimensional ray fans
- No complete information: no skew rays



Sampling of pupil area

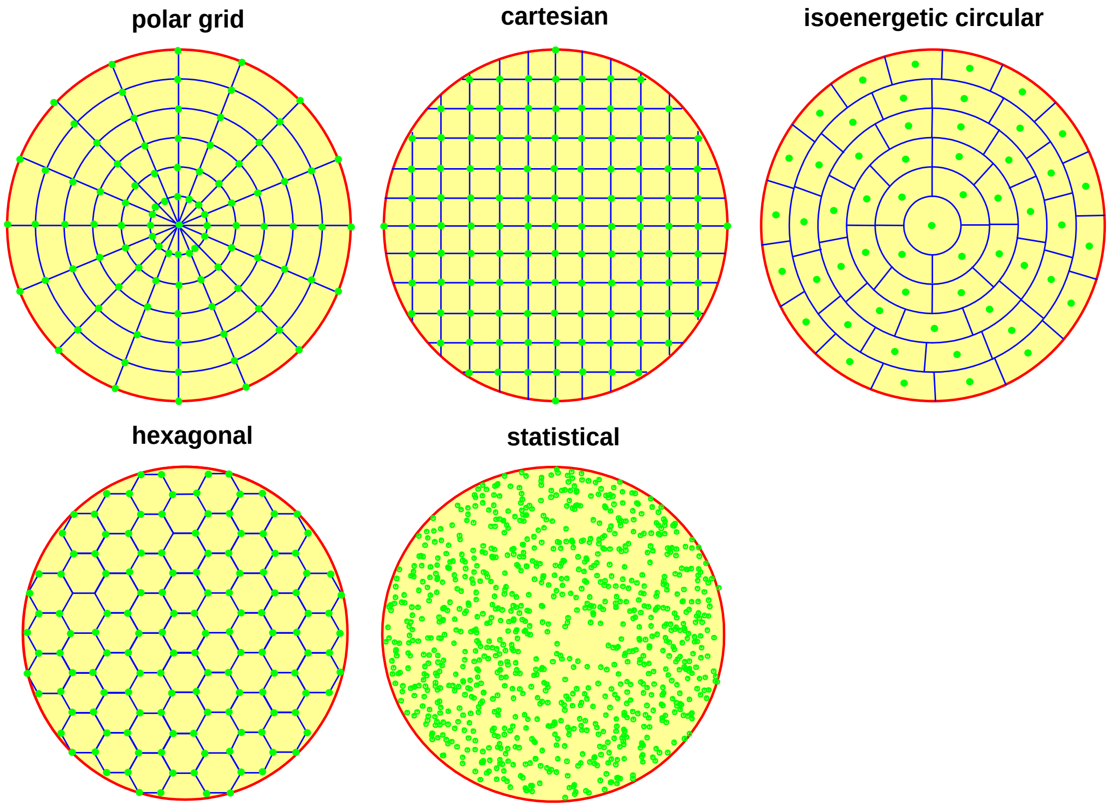
- Pupil sampling in 3D for spot diagram:
  all rays from one object point through all pupil points in 2D

- Light cone completly filled with rays



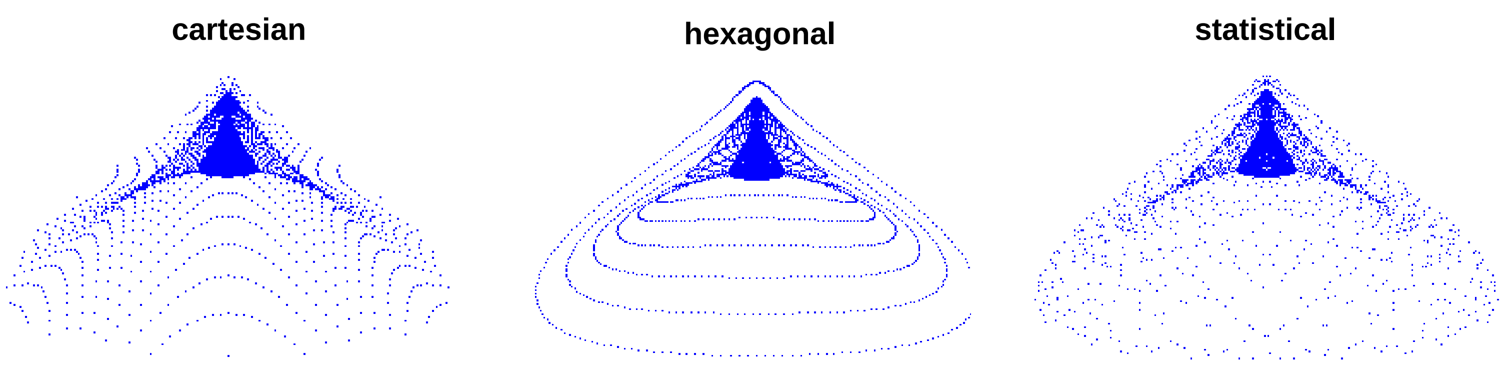
- Different types of sampling with pro and con's:

1. Polar grid: not isoenergetic
2. Cartesian: good for FFT, boundary discretization bad
3. Isoenergetic circular: good
4. Hexagonal: good
5. Statistical: good non-regularity,
   holes ?



Artefacts of pupil sampling

- Artefacts due to regular gridding of the pupil of the spot in the image plane
- In reality a smooth density of the spot is true
- The line structures are discretization effects of the sampling



- Looking for the ray bundle cross sections